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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

THE INFLUENCE OF WALL CONDUCTIVITY ON FILM CONDENSATION WITH INTEGRAL FIN TUBES

by

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September, 1993

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY	2. REPORT DATE 23 September 1993	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE The Influence of Wall Conductivity on Film Condensation With Integral Fin Tubes

5. FUNDING NUMBERS

6. AUTHOR(S) Robert Lee Cobb

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Surface Warfare Center
Carderock Division
Annapolis, Maryard 21402

10. SPONSORING/MONITORING
Code 824

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE
*A

13.

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Results indicated that the performance of a finned tube was strongly dependent on the tube material and weakly dependent on fin geometry. Radiussing the fin root to remove condensate between fins in the unflooded portion (ie, top portion) of a finned tube reduced the heat transfer performance compared to a conventional rectangular shaped integral fin. Experimental data were compared to the models of Beatty and Katz as well as to a modified model of Rose.

14. SUBJECT TERMS (NONE)

15. 263
NUMBER OF PAGES

16.
PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UN

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI STD. 239-18

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The Influence of Wall Conductivity on Film Condensation With Integral Fin Tubes

by

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Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September, 1993

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ABSTRACT

Heat transfer performance of steam condensing on horizontal finned tubes made of copper, aluminum, copper nickel(90/10), and stainless steel(316) was studied using a condenser test rig at both vacuum and atmospheric conditions. Integral fin tubes included conventional rectangular shaped fins as well as rectangular fins having a radiussed root geometry (ie, a fillet radius equal to half the fin spacing). All finned tubes had inner and outer diameters of 12.70mm and 15.88mm respectively, and had a fin thickness of 1.0mm and a fin spacing of 1.5mm. The overall heat transfer coefficient (U_o) was determined *experimentally* and the outside heat transfer coefficient (h_o) was obtained utilizing a modified Wilson Plot procedure.

Results indicated that the performance of a finned tube was strongly dependent on the tube material and weakly dependent on fin geometry. Radiussing the fin root to remove condensate between fins in the unflooded portion (ie, top portion) of a finned tube reduced the heat transfer performance compared to a conventional rectangular shaped integral fin. Experimental data were compared to the models of Beatty and Katz as well as to a modified model of Rose.

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NOMENCLATURE

a	constant defined by equation (4.27) used to determine enhancement
a_f	constant defined by equation (4.27) used to determine enhancement for a finned tube
a_s	constant defined by equation (4.27) used to determine enhancement for a smooth tube
A_{ef}	effective surface area as defined by equation (1.4), m^2
A_{fs}	surface area of fin flank as defined by equation (1.5), m^2
A_{ft}	surface area of fin tip as defined in equation (1.6), m^2
A_i	inside surface area of tube, m^2
A_o	outside surface area of smooth tube, m^2
A_p	fin profile area, m^2
A_u	unfinned surface area as defined in equation (1.7), m^2
b	interfin spacing between fins, m or as a constant defined in equation (4.24)
B_1	constant equal to 2.96
B_f	constant equal to 0.143
B_s	constant equal to 0.143

B_t	constant equal to 0.143
C_i	leading coefficient used for inside heat transfer correlation
c_p	specific heat at a constant pressure, J/(kg*K)
D_{eq}	equivalent diameter as defined in equation (1.1), m
D_i	inside diameter of tube, m
D_f	fin outer diameter, m
D_o	tube outside diameter, m
D_r	finned tube root diameter, m
F	as defined in equation (2.4)
f_f	fraction of unblanked fin flank surface area defined in equation (2.17)
f_s	fraction of the unblanked interfin surface area as defined from [Ref. 8]
f_t	fraction of the unblanked interfin surface area as defined from [Ref. 6]
g	gravitational constant, 9.81 m/s^2
G_f	constant as defined in equation (2.34)
G_s	constant as defined in equation (2.36)
h	heat transfer coefficient, $W/(m^2*K)$ or fin height, m (as specified)
h_{BK}	corrected Beatty and Katz heat transfer coefficient equation (4.33), $W/(m^2*K)$
h_{ef}	effective heat transfer coefficient from Beatty and Katz, equation (1.1), $W/(m^2*K)$
h_{fg}	specific enthalpy of vaporization, J/kg

h_i	inside heat transfer coefficient, $W/(m^2*K)$
h_o	outside heat transfer coefficient, $W/(m^2*K)$
h_{of}	outside heat transfer coefficient for a finned tube, $W/(m^2*K)$
h_{os}	outside heat transfer coefficient for a smooth tube, $W/(m^2*K)$
h_v	effective vertical fin height as defined in equations (2.18) and (2.19)
k	thermal conductivity, $W/(m*K)$
k_c	thermal conductivity of fin material, $W/(m*K)$
k_{cw}	thermal conductivity of cooling water, $W/(m*K)$
k_f	thermal conductivity of condensate film, $W/(m*K)$
K_1	constant as defined in equation (4.18)
K_2	constant as defined in equation (4.19)
L	active length of tube exposed to steam, where the condensation takes place, m
$\bar{L}$	fin flank length as defined in equation (1.3), m
L_1	inlet portion of tube length not exposed to steam, m
L_2	outlet portion of tube length not exposed to steam, m
L_c	corrected fin length as defined in equation (2.12), m
LMTD	log mean temperature difference, K
m	constant defined in equation (4.23)
$\dot{m}$	mass flow rate of the coolant, kg/s

m_1 as defined in equation (4.7a), m^{-1}

m_2 as defined in equation (4.7b), m^{-1}

n_f number of fins per unit length of tube, m^{-1}

Nu Nusselt number

P_1 fin perimeter of inlet portion of tube length, m

P_2 fin perimeter of outlet portion of tube length, m

Pr Prandtl number

q_f heat flux for fin flank, W/m^2

Q_f heat transfer rate for finned tube, W

q_{NUSS} heat flux for smooth tube based on Nusselt theory, W/m^2

Q_{NUSS} heat transfer rate for smooth tube based on Nusselt theory, W

q_s heat flux for interfin spacing, W/m^2

Q_s heat transfer rate for smooth tube, W

q_t heat flux for fin tip, W/m^2

R_1 radius of fin root, m

R_2 radius of fin tip, m

R_{2c} correction for adiabatic fin tip (R_2 + t/2), m

R_a constant used in Bessel function as defined in equation (2.10)

R_b constant used in Bessel function as defined in equation (2.11)

Re Reynolds number

$Re_{2\phi}$ two phase Reynolds number

R_i inside resistance, K/W

R_o	radius of fin tip, m, or outside resistance, K/W
R_r	radius of interfin root, m
R_{TOTAL}	total thermal resistance, K/W
R_w	wall thermal resistance, K/W
s	interfin spacing, m
t	thickness of fin, m
Δt_{vf}	temperature difference across the condensate film, K
ΔT	temperature difference across the condensate film, K
T_1	temperature at tube inlet, K
T_2	temperature at tube outlet, K
T_f	condensate film temperature, K
T_s	constant as defined in equation (2.35), or saturated steam temperature, K
T_{sat}	saturated steam vapor temperature, K
T_t	constant as defined in equation (2.31)
T_w	outer tube wall temperature, K
T_{wo}	outside wall temperature of tube, K
U_∞	vapor velocity, m/s
U_o	overall heat transfer coefficient, $W/(m^2*K)$
X	constant defined in equation (4.22)
Y	constant defined in equation (4.21)
Z	defined from equation (4.14), $W/(m^2*K)$

Greek Symbols

α	leading coefficient for the outside heat transfer coefficient used to determine enhancement
α_f	leading coefficient for the outside heat transfer coefficient for a finned tube used to determine enhancement
α_s	leading coefficient for the outside heat transfer coefficient for a smooth tube used to determine enhancement
β	half angle at fin tip, radians
δ	thickness as defined in equation (2.13), m
η	fin efficiency
η_1	fin efficiency as defined in equation (4.6a)
η_2	fin efficiency as defined in equation (4.6b)
η_f	thermal efficiency of the fin material
ϵ	constant defined in equation (4.17)
ϵ_{AA}	active surface area enhancement ratio for a rectangular shaped finned tube as defined in equation (2.15)
ϵ_{TS}	total surface area enhancement ratio for a rectangular shaped finned tube as defined in equation (2.14)
$\epsilon_{\Delta T}$	enhancement based on a smooth tube equation (2.20)
$\acute{\epsilon}_{AR}$	active surface area enhancement ratio for a radiussed root finned tube as defined in equation (2.38)

ϵ_{TS}	total surface area enhancement ratio for a radiussed root finned tube as defined in equation (2.37)
$\epsilon_{\Delta T}$	heat transfer enhancement ratio for a rectangular shaped finned tube based on Nusselt theory
$\epsilon_{\Delta T,F}$	heat transfer enhancement ratio for a radiussed root finned tube based on Nusselt theory
μ	dynamic viscosity, kg/(m*s)
μ_f	dynamic viscosity of the condensate film, kg/(m*s)
μ_w	dynamic viscosity of the cooling water, kg/(m*s)
ρ	density, kg/m^3
$\tilde{\rho}$	density difference $(\rho_f - \rho_v)$, kg/m^3
ρ_f	density of condensate film, kg/m^3
ρ_v	density of the vapor, kg/m^3
ϕ	condensate flooding angle as defined in equation (1.8)
σ	surface tension of condensate, N/m
ξ	as defined in equation (2.8)
$\xi(\phi)$	as defined in equation (2.26)
Ω	constant defined in equation (4.15)

ACKNOWLEDGEMENTS

The author would like to express his sincere appreciation to Professor Paul J. Marto and Professor Stephen B. Memory for their advice, guidance, and continual support towards the completion of this thesis.

Many thanks is also given to the personnel under the supervision of Mr. Tom McCord for their timely fabrication of all required materials and repairs necessary to complete this endeavor.

Great thanks and appreciation is given to the Professors, in the Mechanical Engineering and Mathematics Department, and Captain W. A. Ericson USN (Curriculum Officer) for their support and understanding during times of personnel hardships during this thesis study period.

The author wishes to extend his greatest thanks and appreciation to his friends (especially Mrs. Pam Davis, Caption Carol A. Roetzler USA, Lcdr. Stan Cunningham USN, and Lt. Pernell Jordan USN). Without their encouragement and support, this thesis project would not have been possible.

I. INTRODUCTION

A. BACKGROUND

With the end of the Cold War, the major interest in the U.S. today is to balance the budget. Part of this process is the reduction of Naval forces. Technology must be developed to meet future threats and costs must remain within the budget. The acquisition of a new system depends primarily on its total cost. Today the priorities of new major acquisitions are 1) cost, 2) performance, and 3) time to become fully operational. Reductions in size and weight have become increasingly important design considerations in the development of every component destined for use aboard United States Navy vessels. Gas turbine propulsion plants have significantly reduced the weight and space for main propulsion machinery aboard surface combatants. However, weight reductions in auxiliary heat exchangers and other large components such as main steam condensers aboard nuclear submarines have progressed more slowly. The use of heat transfer enhancement techniques for condenser tubing pursues this goal. Smaller, more efficient condensers would result in reductions in initial cost, space and weight requirements, and perhaps, operating cost. These heat transfer enhancement techniques can be utilized for other systems as well.

The performance of condenser tubes is determined primarily from the thermal resistances on the coolant side, across the tube wall, on the vapor side, and due to fouling. Each resistance can be reduced to minimize its effect, which in turn, enhances the overall heat transfer rate of the system. The major or dominant resistance in general is on the inside, which can be reduced by suitable internal enhancement techniques. The wall thermal resistance can be reduced by decreasing the wall thickness or changing the tube material.

Enhancement techniques are categorized into two major groups, active and passive. Passive techniques include internal helical ribbing, displaced promoters (the use of wire mesh or Heatex inserts), and finned surfaces. Active techniques are the use of devices that add energy to the system and not are part of this thesis. This thesis will focus on externally finned surface condenser tubing. Earlier studies with finned tubing showed little improvement for steam condensation due to the large amount of condensate retained between the fins and the underprediction of the heat transfer coefficient. Better understanding of the two phase heat transfer phenomena and improved models have renewed the interest of integral finned tubes for steam condensers.

B. CONDENSATION

Since 1916, researchers have attempted to improve the simple model of Nusselt to predict the heat transfer

coefficient for condensation on horizontal tubes. Nusselt's theory was based on a plain tube, and neglected the effect of vapor shear. In 1948, Beatty and Katz [Ref. 1] developed an analytical model to predict the outside heat transfer coefficient for an integral finned tube. Their model accounted for the thermal conductivity (efficiency) of the tube material. Their basic equation is shown below:

$$h=0.689\left[\frac{k_f^3\rho_f^2 g h_{fg}}{\mu_f}\right]^{1/4}\left[\frac{1}{\Delta t_{vf}}\right]^{1/4}\left[\frac{1}{D_{eq}}\right]^{1/4} \tag{1.1}$$

The equivalent diameter, D_{eq}, can be calculated from [Ref. 2] as follows:

$$\left[\frac{1}{D_{eq}}\right]^{1/4}=1.30\eta_f\frac{A_{fs}}{A_{ef}}\frac{1}{\bar{L}^{1/4}}+\eta_f\frac{A_u}{A_{ef}}\frac{1}{D_o^{1/4}}+\frac{A_u}{A_{ef}}\frac{1}{D_r^{1/4}} \tag{1.2}$$

where:

$$\bar{L}=\pi\frac{(D_o^2-D_r^2)}{4D_o} \tag{1.3}$$

$$A_{ef}=\eta_f A_{fs}+\eta_f A_{ft}+A_u \tag{1.4}$$

$$A_{fs}=\frac{2n_f\pi\,(D_o^2-D_r^2)}{4} \tag{1.5}$$

$$A_{ft}=n_f\pi D_o t \tag{1.6}$$

$$A_u=n_f\pi D_r s \tag{1.7}$$

and η is the thermal efficiency of the fins. The Beatty and Katz model neglects the effects of surface tension of the condensate and the vapor shear. These forces thin the condensate film between the fins. Beatty and Katz tested horizontal integral spiral-finned tubes made from copper and nickel using a variety of fluids: propane, n-butane, n-pentane, methyl chloride, sulfur dioxide, and freon-22. These fluids have small surface tension effects. The predicted heat transfer coefficients were within +7.2% and -10.2% of the values determined from the overall heat transfer data.

Rudy and Webb [Ref. 3] developed an analytical model that predicts the amount of condensate retention on a horizontal integral finned tube. The model showed that a significant portion of the surface can be covered by retained condensate. Honda et al. [Ref. 4] recommended, for rectangular-shaped fins, the condensate flooding angle ϕ be computed from the relationship,

$$\phi=\cos^{-1}\left[\frac{4\sigma}{\rho g s D_f}-1\right] \tag{1.8}$$

The condensate flooding angle is measured from the top of the finned tube as shown in Figure 1.1. For rectangular finned tubes, retained condensate forms a wedge at the base of the fin root. This condensate film wedge increases in thickness from the top to the bottom of the tube. The condensate flooding angle is the point in which the condensate wedge covers the entire fin flanks and interfin spacing. The shaded area, in Figure 1.1, represents the retained condensate wedge. It is assumed that no heat transfer occurs in the shaded area. The unshaded areas, in Figure 1.1, are the uncovered fraction of the fin flanks and interfin spacing for heat transfer. For a fin spacing of 1.5mm, height of 1mm, and thickness of 1mm, $\phi \approx 82.08^0$ for steam at 100^0C. Yau, Cooper, and Rose [Ref. 5] also Wanniarachchi, Marto and Rose [Ref. 6] studied the effect of fin spacing and the resulting flooding angle for maximum vapor-side enhancement. They concluded that for a copper rectangular integral finned tube, the optimum fin spacing is ≈1.5mm for a fin thickness of 1mm and height of 1mm. Masuda and Rose [Ref. 7] conducted a detailed study of the static configuration of the retained liquid using equation (1.8). The observed heat transfer enhancement was higher than expected and attributed it to the surface tension effects.

Masuda and Rose examined the enhancement ratio for the total surface area for a rectangular finned and a radiussed root finned tube. They also studied the active surface area enhancement using the condensate retention angle to determine the flooded and unflooded fraction of the fin surface area. The flooded area was also called the blanked area by retained liquid. Rose [Ref. 8] modified the Nusselt equation to account for the gravitational and surface tension forces for the condensate. The enhancement ratios are based on the same temperature differential using the blanked and unblanked fraction of the fin surfaces. However, they did not include the efficiency of the material.

Due to the complexity of the steam condensation problem for horizontal finned tubes, no one model has been developed that correlates the efficiency of the material along with other effects of the surface tension of the condensate, the gravity force of the condensate, steam vapor velocities, and the condensate flooding angle.

C. NAVAL POSTGRADUATE SCHOOL CONDENSATION RESEARCH

This thesis continues the research that was begun under sponsorship of the National Science Foundation at the Naval Postgraduate School (NPS). The apparatus constructed by Krohn [Ref. 9], June 1982, was modified by Swensen [Ref. 10]. The basic operation of the system remained unchanged. Copper horizontal integral finned tubes of various fin geometries and

tube diameters have been extensively studied at NPS independently. Rectangular finned tubes were studied by Coumes [Ref. 11], Van Petten [Ref. 12], and Guttendorf [Ref. 13]. Mitrou [Ref. 14], in addition to copper, studied copper nickel and aluminum rectangular fins. Detailed studies are required comparing different rectangular and fillet radial fins of different materials. The additional studies will help determine the best material and fin geometry for a particular operating system.

D. OBJECTIVES OF THIS THESIS

The main objectives of this thesis are:

1. Obtain repeatable data for steam condensation on horizontal tubes having rectangular shaped radial fins made of copper, aluminum, copper nickel, and stainless steel, showing the effects on the thermal conductivity of the materials.

2. Compare the data for rectangular shaped finned tubes to radiussed root finned tubes to examine the influence of the radius on the enhancement for each material.

3. Compare the experimental data to the predicted values using existing theoretical models of Beatty and Katz [Ref. 1]and Rose [Ref. 8].

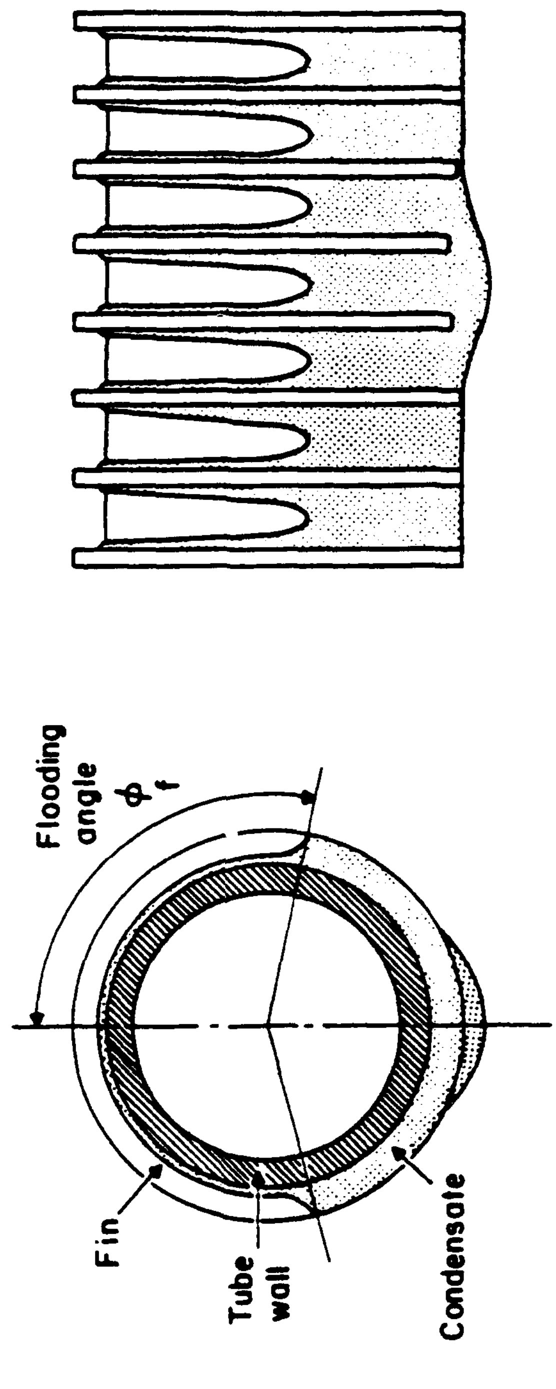

Figure 1.1 Schematic of Condensate Retention Angle on Finned Tubes and Condensate Wedge (illustrated by the gray sections)

II. LITERATURE SURVEY

A. CONDENSATION

Condensation has been intensely studied as a heat transfer mechanism. The developments in condenser tubing and compact electronic equipment continued the requirement for experimental and theoretical research in this field.

There are two fundamental modes of condensation, filmwise and dropwise. Dropwise condensation, as its name states, is the condensing of the vapor into discrete liquid droplets on the surface. As the droplets grow, they coalesce until they are large enough to be removed by gravity or vapor shear. Filmwise condensation creates a continuous liquid film over the entire surface area. The heat transfer rate for the tube is reduced due to the relatively thick condensate film thickness. Dropwise condensation can produce a heat transfer rate as much as an order of magnitude larger than that associated with filmwise condensation. Since the heat transfer rate is lower for the filmwise condensation, condenser design calculations are normally based on this more conservative mode of condensation [Ref. 15]. Complete filmwise condensation may be difficult to produce. The tube must be free of oils, greases and non-wetting chemical deposits.

B. HEAT TRANSFER CORRELATIONS

The heat transfer coefficients for condensation on horizontal tubes are difficult to accurately predict. A suitable theoretical model must be developed and utilized.

1. Horizontal Smooth Tubes

Nusselt [Ref. 16] developed the foundation for the study of filmwise condensation on horizontal tubes in 1916. His correlation was developed for a quiescent vapor condensing on a single horizontal tube. He neglected shear forces and the thermal conductivity of the tube material. The shear forces of the liquid cause the condensate film to increase in thickness from the top of the tube to the bottom. Gravity force assists in draining the condensate around the sides of the tube circumference. The heat flux changes around the circumference of the tube with the maximum heat flux at the top of the tube where the film is the thinnest with no heat transfer at the tube bottom where the film is the thickest. Nusselt's equation for the average outside heat transfer coefficient around the tube is the following:

$$h_o=0.728\left[\frac{k_f^3 g \rho_f(\rho_f-\rho_v)}{\mu_f D_o(T_{sat}-T_{wo})}\right]^{1/4} \tag{2.1}$$

where the fluid properties are evaluated at the film temperature, defined as:

$$T_f = \frac{1}{3} T_{sat} + \frac{2}{3} T_{wo} \tag{2.2}$$

Nusselt's theory has been extensively studied since 1916. Even with his simplifying assumptions, his work has been found to be generally valid [Ref. 17, 18]. His theory was also found to be accurate for cases which do not conform to his original assumptions, such as variable wall temperature [Ref. 19]. One of the major problems in applying Nusselt's theory in the design of condensers is the assumption of a quiescent vapor. While in theory the assumption of a stationary vapor can be justified, steam condensers operate under conditions where the vapor is travelling at some velocity.

With the vapor in motion, shear forces are developed which thin the condensate film and increase the outside heat transfer coefficient. Early theoretical work by Shekriladze and Gomelauri [Ref. 20] accounted for vapor shear forces. They assumed that the primary contribution to the surface shear stress was due to the change in momentum across the liquid-vapor interface. This resulted in the following equation to approximate the mean Nusselt number:

$$\frac{Nu}{Re_{2\phi}^{1/2}} = 0.64\,(1 + (1 + 1.69F)^{1/2})^{1/2} \tag{2.3}$$

where:

$$F=\frac{gD_o\mu_f h_{fg}}{U_\infty^2 k_f(T_{sat}-T_{wo})} \tag{2.4}$$

and the two phase Reynolds number is given by:

$$Re_{2\phi}=\frac{\rho_f U_\infty D_o}{\mu_f} \tag{2.5}$$

Lee and Rose [Ref. 21] compared vapor shear models with experimental results and found that the Shekriladze-Gomelauri results were more conservative than other researchers due to their simplified approximation for the interfacial shear stress. Fujii et al. [Ref. 22], in a more recent study, performed an extensive development of the shear forces on the outside of a horizontal tube. From experimental data, they also developed a simple empirical formulation for the condensation of steam on a horizontal tube which includes vapor velocity effects:

$$\frac{Nu}{Re_{2\phi}^{1/2}}=0.96F^{1/5} \tag{2.6}$$

where F and $Re_{2\phi}$ are defined in equations (2.4) and (2.5). For situations where the surface shear forces dominate, as for

steam, equation (2.6) more accurately predicts the vapor side heat transfer coefficient than equation (2.3).

As discussed previously, the primary modes of external tube enhancement covered in this study are rectangular fins and fillet radius fins. There are advantages and disadvantages for each depending on the environment or operating conditions in which the tube is to be used.

2. Rectangular-Shaped Finned Tubes

Fins can be attached to the surface of smooth tubes to increase the heat transfer between the surface and the vapor medium. The enhancement is due primarily to the increase in surface area. The fins also channel the flow of the condensate. As the condensate forms and travels to the root of the fin, it's film varies in thickness. The film at top of the fin is generally thinner than at the bottom. This thinning increases the heat transfer rate of the tube. Part of the increase in enhancement is therefore caused by the surface tension of the condensate and the vapor shear forces.

The fins used by Beatty and Katz [Ref. 1] were spiral. However, their theory applies for rectangular-shaped annular fins. The efficiency equation used by Beatty and Katz [Ref. 1] was not listed, but the efficiency for a rectangular-shaped annular fin can be used (equation (2.7)) from [Ref. 23]:

$$\eta_f = \frac{\sqrt{2}/\xi}{(1+r_{2c}/r_1)}\left[\frac{I_1(R_a\xi)K_1(R_b\xi)-I_1(R_b\xi)K_1(R_a\xi)}{I_1(R_a\xi)K_0(R_b\xi)+I_0(R_b\xi)K_1(R_a\xi)}\right] \qquad (2.7)$$

where:

$$\xi = L_c^{3/2}\sqrt{h/(k_c A_p)} \tag{2.8}$$

$$A_p = 2\delta L_c \tag{2.9}$$

$$R_a = \sqrt{2}/(1 - R_1/R_{2c}) \tag{2.10}$$

$$R_b = (R_1/R_{2c})\,R_a \tag{2.11}$$

where L_c is the corrected length of the fin determined by:

$$L_c = L + t/2 \tag{2.12}$$

$$\delta = \frac{t}{2} \tag{2.13}$$

Equation (2.7) assumes an adiabatic fin tip (no heat transfer through the fin tip). Figure 2.1 is a sketch of an annular fin of rectangular profile used to defined the dimensions in the above equations. The efficiency of finned tubes not only depends on the tube material but also the fin tube geometry. Figure 2.2 illustrates the change in efficiency of a fin as the geometry and the thermal conductivity of the material changes. The higher the thermal conductivity of a material, the higher the efficiency of the material.

Gregorig [Ref. 24] discovered that fins generated a surface tension force which tended to thin the condensate at the tip and thicken it between the fins. Masuda and Rose [Ref. 6] examined condensate retention on horizontal finned tubes. They defined an enhancement ratio for the increase in surface area by dividing the total surface area of a rectangular-shaped fin by the area of a smooth tube of the root diameter:

$$\varepsilon_{TS}=\frac{R_r b+(R_o^2-R_r^2)+R_o t}{R_r(b+t)} \tag{2.14}$$

The first term in the numerator is the area for the interfin space, the middle term is the fin flank surface area, and the third term is the fin tip surface area. The condensate flooding angle equation (1.8) was used to determine the fraction of the fin flank and tip area blanked by the condensate film. They defined an "active area enhancement" for a rectangular-shaped finned tube by dividing the unblanked finned tube surface area by the surface area of a smooth tube of root diameter. It is given by equation (2.15):

$$\varepsilon_{AA}=\frac{R_r b\phi(1-f_t)+(R_o^2-R_r^2)\phi(1-f_f)+\pi R_o t}{\pi R_r(b+t)} \tag{2.15}$$

The first term in the numerator is the unblanked area of the

interfin space, the middle term is the unblanked area of the fin flanks, and the third is the fin tip area. The tip was assumed to be free of condensate. The fraction of the unblanked surface areas covered by condensate is given by:
For the interfin space,

$$f_t=\left(\frac{2\sigma}{\rho g R_r b}\right)\left(\frac{\tan(\phi/2)}{\phi}\right), \tag{2.16}$$

and for the fin flank,

$$f_f=\left(\frac{\sigma}{\rho g R_r h}\right)\left(\frac{\tan(\phi/2)}{\phi}\right) \tag{2.17}$$

Honda et al [Ref. 25] and Adamek and Webb [Ref. 26] have formulated models for film condensation on horizontal finned tubes, but they are difficult to use. Recently, Briggs, Wen, and Rose [Ref. 27] conducted a detailed review of the accuracy of various models to measure heat transfer for condensation on horizontal integral finned tubes. The simple model of Beatty and Katz [Ref. 1] does not account for surface tension effects. The Adamek and Webb model [Ref. 26] included an approximate surface tension effect and the result was an improved enhancement prediction. They concluded the best model to predict the heat transfer measurements is the Honda et al model [Ref. 25] which accounts for both the condensate

flooding and the enhancing effect of surface tension drainage from the fins. This is the most accurate model for predicting the heat transfer measurements for steam condensation on horizontal integral finned tubes. However, the model is very complex which limits its use. Rose [Ref. 8] proposed a "very simple model" to approximate the vapor side heat transfer coefficient for condensation on low integral finned tubes. His model included surface tension and condensate flooding, but neglected the resistance due to conduction in the fin material. Rose [Ref. 8] formulated a simpler semi-empirical equation for calculating the vapor-side enhancement ratio for condensation on low-finned tubes. His equation accounts for the condensate flooding angle, as well as gravity and surface tension effects. He noted that if the ratio of $\sigma\cos\beta/(\rho g b D_o)$ is greater than 0.5, the interfin space is fully flooded and the condensate retention angle is zero. The Nusselt theory was modified by replacing the fin height with the vertical fin height determined from equation (2.18) or (2.19).

For $\phi \leq \pi/2$:

$$h_v = h\phi\sin\phi \qquad (2.18)$$

For $\phi \geq \pi/2$:

$$h_v = h\phi/(2-\sin\phi) \qquad (2.19)$$

The enhancement ratio for the same ΔT was determined by dividing the heat transfer rate of the finned tube (with blanked areas) by the heat transfer rate of a smooth tube of the same root diameter and ΔT:

$$\varepsilon_{\Delta T}=\frac{Q_f/\Delta T}{Q_s/\Delta T}=\frac{Q_f}{Q_s} \tag{2.20}$$

where the heat transfer rate for the rectangular finned tube is,

$$Q_f=\pi D_o t q_t+\frac{\phi}{\pi}\left[\frac{(1-f_f)\,\pi\,(D_o^2-D_r^2)}{2}q_f+(1-f_s)\,\pi D_r s q_s\right] \tag{2.21}$$

and the heat transfer rate of a smooth tube of root diameter D_r was determined from Nusselt theory,

$$Q_S=\pi D_r\,(s+t)\,q_{nuss}. \tag{2.22}$$

In the above expressions, the heat transfer fluxes are:

Nusselt theory, for a smooth tube of root diameter D_r:

$$q_{nuss}=0.728\left[\frac{\rho h_{fg}k^3\Delta T^3}{\mu}\,\frac{\tilde{\rho}g}{D_r}\right]^{1/4} \tag{2.23}$$

for the fin flanks:

$$q_f=\left[\frac{\rho h_{fg}k^3\Delta T^3}{\mu}\left[\frac{0.943^4\tilde{\rho}g}{h_v}+\frac{B_f\sigma}{h^3}\right]\right]^{1/4} \tag{2.24}$$

for the interfin space:

$$q_s=\left[\frac{\rho h_{fg}k^3\Delta T^3}{\mu}\left[\frac{(\xi(\phi))^3\tilde{\rho}g}{D_r}+\frac{B_s\sigma}{s^3}\right]\right]^{1/4} \tag{2.25}$$

where $\xi(\phi)$, the mean condensate film thickness from the top of the horizontal tube to the condensate flooding angle ϕ is;

$$\xi(\phi)=0.874+0.1991x10^{-2}\phi-0.2642x10^{-1}\phi^2+0.5530x10^{-3}\phi^3-0.1363x10^{-2}\phi^4 \tag{2.26}$$

for the fin tip:

$$q_t=\left[\frac{\rho h_{fg}\Delta T^3}{\mu}\left[\frac{0.728^4\tilde{\rho}g}{D_o}+\frac{B_t\sigma}{t^3}\right]\right]^{1/4} \tag{2.27}$$

$$f_f=\frac{2\sigma}{\rho g D_r h}\frac{\tan(\phi/2)}{\phi} \tag{2.28}$$

$$f_s=\left(\frac{4\sigma}{\rho g D_r s}\right)\left(\frac{\tan(\phi/2)}{\phi}\right) \tag{2.29}$$

Using the above relationships, the enhancement ratio for constant (ΔT) can be rearranged into equation (2.30):

$$\varepsilon_{\Delta T}=\frac{D_o}{D_r}\frac{t}{(s+t)}T_t+\frac{\phi}{\pi}(1-f_f)\left[\frac{D_o^2-D_r^2}{2D_r(s+t)}\right]T_f+\frac{\phi}{\pi}(1-f_s)B_1\frac{s}{(s+t)}T_s \tag{2.30}$$

where

$$T_t=\left[\frac{D_r}{D_o}+\frac{B_t G_t}{0.728^4}\right]^{1/4} \tag{2.31}$$

$$G_t=\frac{\sigma D_r}{\bar{\rho} s t^3} \tag{2.32}$$

$$T_f=\left[\left[\frac{0.943}{0.728}\right]^4\frac{D_r}{h_v}+\frac{B_f G_f}{0.728^4}\right]^{1/4} \tag{2.33}$$

$$G_f=\frac{\sigma D_r}{\bar{\rho} g h^3} \tag{2.34}$$

$$T_s=\left[\frac{(\xi(\phi))^3}{0.728^4}+\frac{B_s G_s}{0.728^4}\right]^{1/4}, \qquad (2.35)$$

and

$$G_s=\frac{\sigma D_r}{\tilde{\rho} g s^3}. \qquad (2.36)$$

Note that this enhancement model neglects the conductivity of the fin material and requires the specification of four coefficients B_1, B_f, B_s and B_t. Rose compared calculated values from equation (2.30) to existing experimental data for a copper fin tube using R-113 and steam condensing vapors. After extensive curve-fitting, the constants were determined to be $B_1=2.96$ and $B_t= B_f= B_s= 0.143$. For steam, the theoretical enhancement values were within ~25% of the experimental enhancement results.

3. Radiussed Root Finned Tubes

Radiussed root fins are rectangular shaped fins with the sharp base corners removed. Figure 2.3 shows the radiussed root finned tubes and the rectangular shaped finned tube used in this study. The finned tube root was rounded with a radius equal to half the fin spacing. Radiussed root finned tubes have less total surface area than rectangular shaped finned tubes. Masuda and Rose [Ref. 7] defined the

total surface area enhancement of a radiussed root finned tube as:

$$\varepsilon_{TS}=\frac{\left[R_o^2-\left(R_r+\frac{b}{2}\right)^2\right]+\frac{\pi b}{2}\left[R_r+\frac{b}{2}\left(1-\frac{2}{\pi}\right)\right]+R_o t}{R_r(b+t)} \tag{2.37}$$

However, by radiussing the fin root, there is no condensate wedge at the base of the fin that occurs in rectangular fins. Thus, more of the surface area remains "active". They defined the "active area enhancement" as:

$$\varepsilon_{AR}=\frac{\left[R_o^2-\left(R_r+\frac{b}{2}\right)^2\right]\left(\frac{\phi}{\pi}\right)+\left[R_r+\frac{b}{2}\left(1-\frac{2}{\pi}\right)\right]\frac{b\phi}{2}+R_o t}{R_r(b+t)} \tag{2.38}$$

Briggs, Wen and Rose [Ref. 28] continued the investigation of the effect of radiussed root for rectangular shaped finned tube. They tested two radiussed root tubes and two rectangular shaped finned tubes made of copper. With a high thermal conductivity material, they expected a large increase in experimental enhancement due to the increase in the "active surface area" for the radiussed root tube. The enhancement ratio of the "active surface area" for a radiussed root tube (ϵ_{AR}) and a rectangular finned tube (ϵ_{AA}), (ϵ_{AR} / ϵ_{AA}), was 1.53 for steam with a 1.5mm fin spacing and 1.42 for a 1.0mm fin

spacing. The enhancement ratio for the 1.0mm fin spacing agreed well with the experimental enhancement heat transfer ratio ($\epsilon_{\Delta T,F}$ / $\epsilon_{\Delta T}$) of 1.33, but the experimental heat transfer enhancement ratio for the 1.5mm fin spacing was only 1.09. They felt the small corresponding increase in enhancement for the 1.5mm spacing seemed somewhat anomalous and intend to repeat the data.

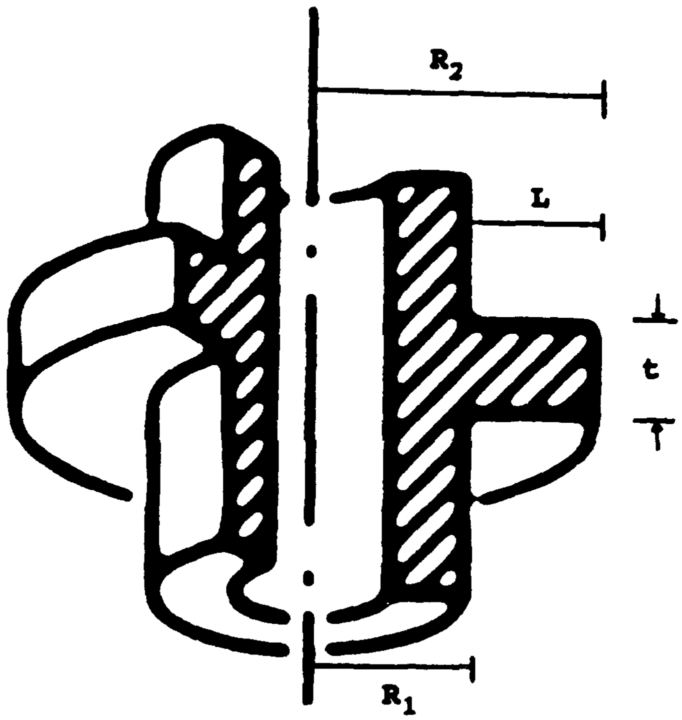

Figure 2.1 Schematic of Annular Fin of Rectangular Profile

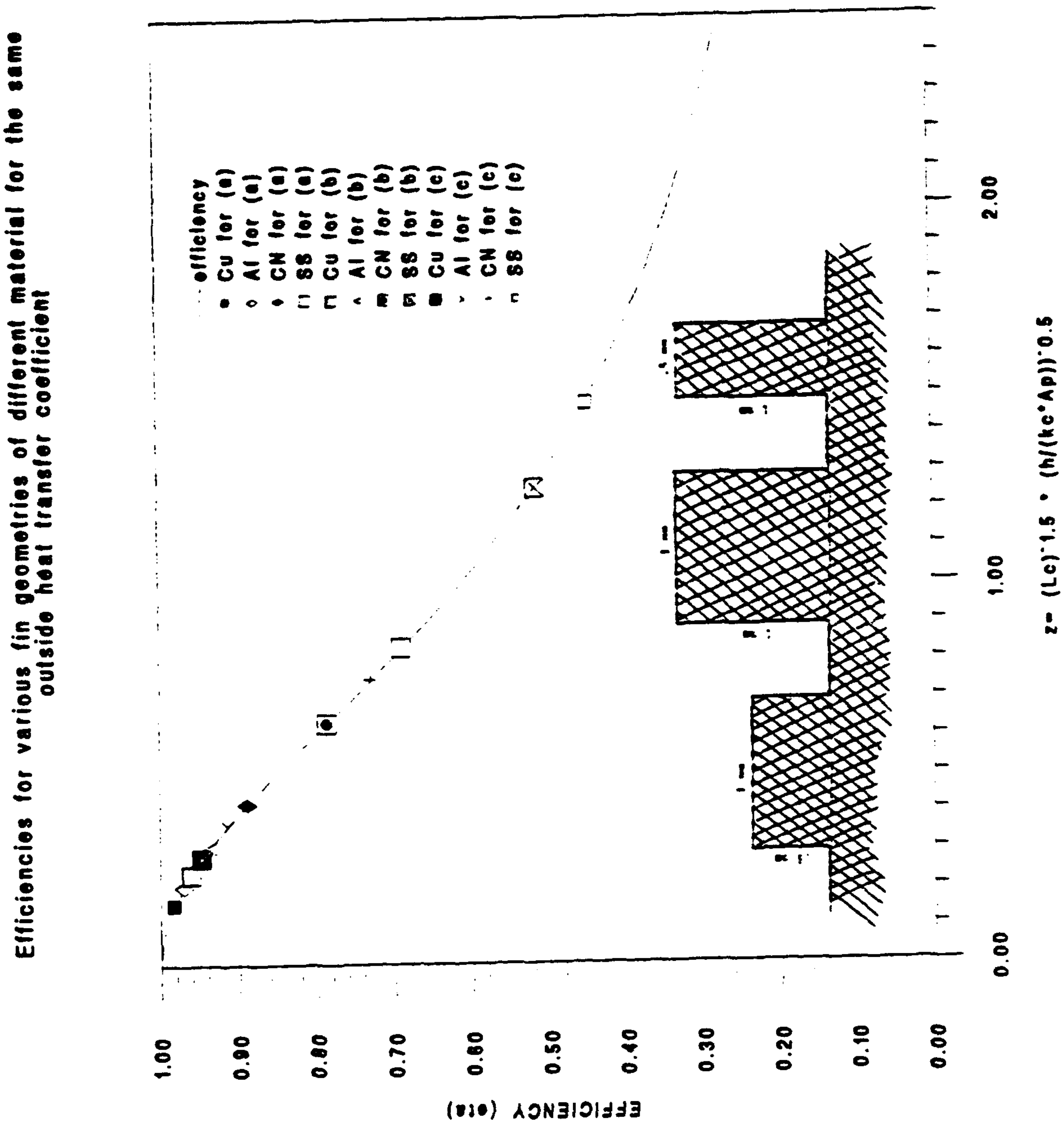

Figure 2.2 Efficiencies for various Fin Geometries for Different Materials for the same Outside Heat Transfer Coefficient (h_o= 10000 ($W/(m^2*K)$))

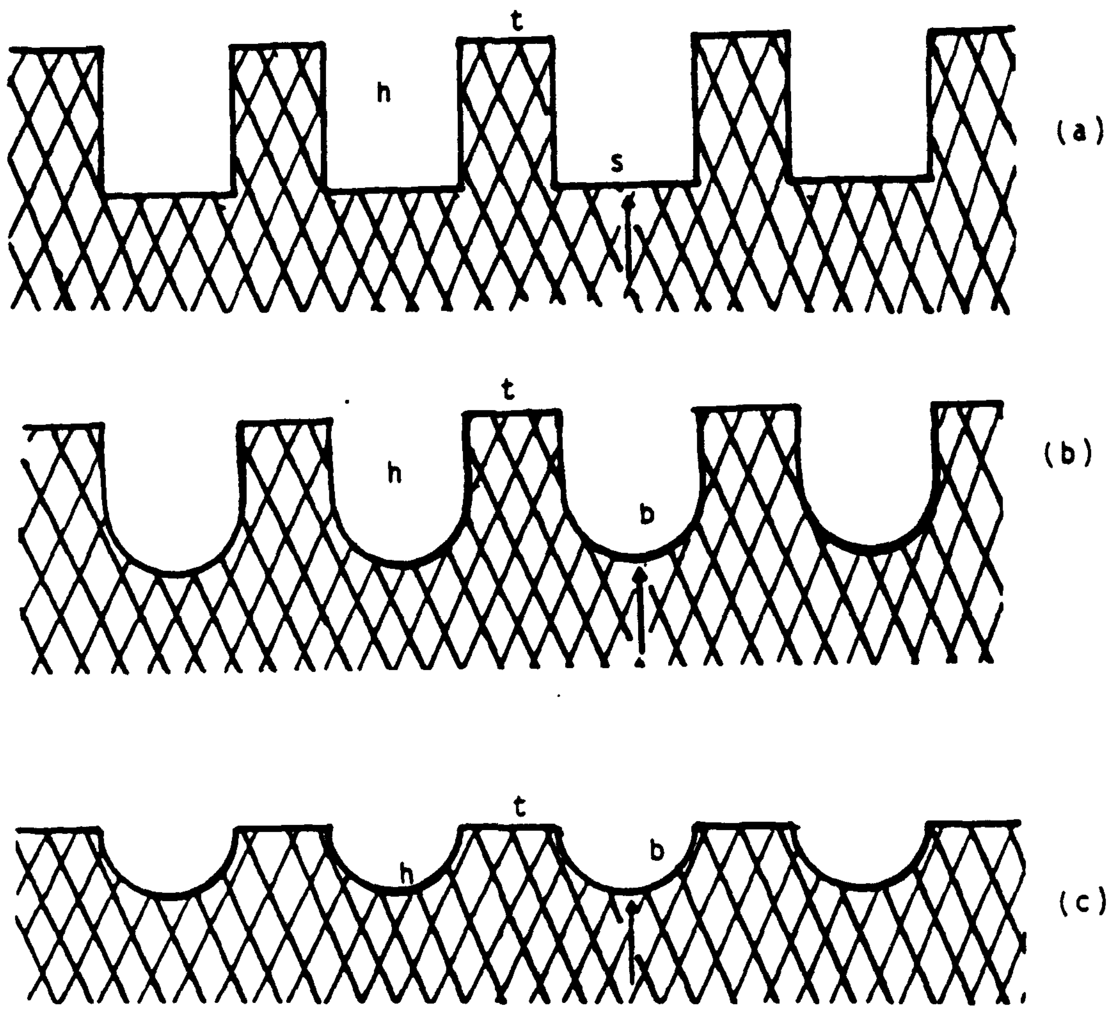

Figure 2.3 Dimensions for Finned Tubes Tested (a) rectangular shaped finned tube D_r= 13.88mm, h= 1.0mm, s= 1.5mm, and t= 1.0mm; (b) deep radiussed root finned tube D_r= 13.88mm, h= 1.0mm, s= 1.5mm, t= 1.0mm, and b= 0.75mm; (c) shallow radiussed root finned tube D_r= 14.38mm, h= 0.75mm, s= 1.5mm, t= 1.0mm, and b= 0.75mm

III. EXPERIMENTAL APPARATUS

A. SYSTEM OVERVIEW

The apparatus is basically the same as designed by Krohn [Ref. 9] and modified by Swensen [Ref. 10]. Figure 3.1 is a schematic of the test apparatus. The boiler is fabricated from a .3048m diameter Pyrex Glass tube with ten 4-kw, Watlow immersion heaters. The boiler can be filled by gravity drain or vacuum drag from a distilled water tank through a fill/drain valve. The steam travels vertically from the boiler section into a 2.13m long section of Pyrex tubing, with a diameter of 0.15m. It then travels through two 90^0 elbows that act as a moisture separator and direct the flow down to the stainless steel test section. The Pyrex glass sections are insulated to reduce the heat lost to the environment.

The test section is fitted with openings for Teflon and nylon seals which support the horizontal tube and provide the coolant flow path. Figures 3.1 and 3.2 illustrate the cooling flow path and the temperature probes. Cooling water is provided to the test tube via two positive displacement centrifugal pumps. The pumps discharge to a flowmeter via a common line. Cooling water flow was controlled by a throttle valve up stream of the flowmeter. Temperature in the sump is controlled by supplementing tap water. The cooling water sump

serves two purpose, 1) to provide the coolant for the test tube and 2) to provide a heat exchanger for the vacuum line. Excess steam, the steam not condensed by the horizontal tube, flows across the auxiliary condenser.

The auxiliary condenser section is also fabricated of Pyrex glass. Ambient temperature water which flows through an internal copper tube was used to condense the remaining steam. A suction port is located in the bottommost part of this section to remove air and other non-condensible gases. These gases are expelled to the atmosphere via a vacuum line to a plexiglas tank connected to the vacuum pump. A layout of the purging system is shown in Figure 3.3. Gravity drains the condensed steam back to the boiler.

B. SYSTEM INSTRUMENTATION

The power for the immersion boiler is provided by a 440 Volt silicon controlled rectifier mounted within the electrical switchboard. Figure 3.4 is a line diagram of the power supply. A feedback loop was installed to maintain a constant power supply to the boiler. Part of the voltage was used for an emf sign for a pressure conversion. This was one of the three means to determine the pressure in the test section. The other two are 1) a Setra model 204 pressure transducer and 2) a direct reading from a Heise pressure gage (this was used only as a visual reference).

The vapor temperature was measured by a Type-T thermocouple located upstream of the horizontal tube being tested or calculated as a function of the voltage reading from the pressure transducer. Cooling water temperatures were calculated from the inlet and outlet temperatures of the flow through the test tube. The temperature differential of the cooling water used was either from a Teflon coated Type-T thermocouple, a ten junction thermopile, or a HP 284A quartz crystal thermometer. The location of the probes are illustrated in Figures 3.1 and 3.2.

An HP-3497A data acquisition system links the voltage readings from the various elements to an HP-9826A computer, except for the quartz thermometer which is read directly. The HP-9826A computer used the program "DRPALL", listed in Appendix A, to collect, process and store data. The computer stepped through the voltage output channels of the acquisition unit and used it's internal functions to convert the emf voltage signal into useful data.

C. TUBES TESTED

A total of fifteen tubes were manufactured for this thesis, thirteen finned tubes and two smooth tubes. The finned tubes were made of copper, aluminum, copper nickel (90/10),and stainless steel (316). There were three types of finned tubes:

1. Type I, standard rectangular shaped finned tube, root diameter of 13.88mm, fin height 1.0mm.

2. Type II, rectangular shaped finned tube with a radiussed root, tube diameter at the root was the same as the rectangular shaped finned tube (13.88mm) and the fin height was 1.0mm from the fin root. This tube was referred to as the "deep fillet fin tube" during the test procedures.

3. Type III, rectangular shaped finned tube with a radiussed root, tube diameter of 14.38mm. The fin height of this tube was the same as the radius of radiussed root (0.75mm). This finned tube was referred to as the "shallow fin tube".

The thermal conductivities for the tube materials used are listed in TABLE I. The values were obtained by curve-fitting the data in [Ref. 29] for the temperature range of the study. Figure 3.5 illustrate the relative size and the geometry of the tubes. Figures 3.6, 3.7, and 3.8 are photographs of the rectangular shaped finned tube, deep radiussed root finned tube, and shallow radiussed root finned tubes, respectively. The dark lines in the radiussed root photographs are light reflections from the curvature of the fin root and not the actual machining of the finned tube. The inside diameter, D_i, of all tubes tested was 12.7mm. All the finned tubes had an outside diameter of 15.88mm for the fins. The first smooth tube made had an outside diameter, D_o, of 13.88mm. It was damaged during testing and a second (stiffer) tube was manufactured, outside diameter of 14.38mm. The tube was filled with "Cerabond 375^0" to reinforce the tube wall while machining. This reinforcing compound was removed after

machining by heating the tube. All residue was removed during tube preparation.

All tubes were tested with a Heatex insert (wire mesh promoter) to increase the accuracy of the results. Minor tool marks inside the tube from the machining operation were neglected due to the increased turbulence by the Heatex insert. TABLE II is a list of all tubes tested and their geometry.

TABLE I. THERMAL CONDUCTIVITIES OF TUBES TESTED.

MATERIAL	**THERMAL CONDUCTIVITY (kc) (W/(m*K))**
COPPER	390.8
ALUMINUM	231.8
COPPER-NICKEL (90/10)	55.3
STAINLESS STEEL	14.3

TABLE II. DIMENSIONS AND MATERIALS FOR TUBES TESTED.

Tube No.	Tube Type	Tube Material	Root Diameter (mm)	Fin Height (mm)	Outer Diameter (mm)	Fin Thickness (mm)	Fin Spacing (mm)
1	Rectangular Fin	Copper (Pure)	13.88	1.00	15.88	1.00	1.50
2	Shallow Fillet	Copper (Pure)	14.38	0.75	15.88	1.00	1.50
3	Deep Fillet	Copper (Pure)	13.88	1.00	15.88	1.00	1.50
4	Deep Fillet	Copper Nickel (90/10)	13.88	1.00	15.88	1.00	1.50
5	Shallow Fillet	Copper Nickel (90/10)	14.38	0.75	15.88	1.00	1.50
6	Rectangular Fin	Copper Nickel (90/10)	13.88	1.00	15.88	1.00	1.50
7	Deep Fillet	Stainless Steel (316)	13.88	1.00	15.88	1.00	1.50
8	Shallow Fillet	Stainless Steel (316)	14.38	0.75	15.88	1.00	1.50
9	Rectangular Fin	Stainless Steel (316)	13.88	1.00	15.88	1.00	1.50
10	Rectangular Fin	Aluminum (Pure)	13.88	1.00	15.88	1.00	1.50
11	Deep Fillet	Aluminum (Pure)	13.88	1.00	15.88	1.00	1.50
13	Shallow Fillet	Aluminum (Pure)	14.38	0.75	15.88	1.00	1.50
OD1	Smooth	Copper (Pure)	13.88	NA	13.88	NA	NA
SMTH	Smooth	Copper (Pure)	14.38	NA	14.38	NA	NA

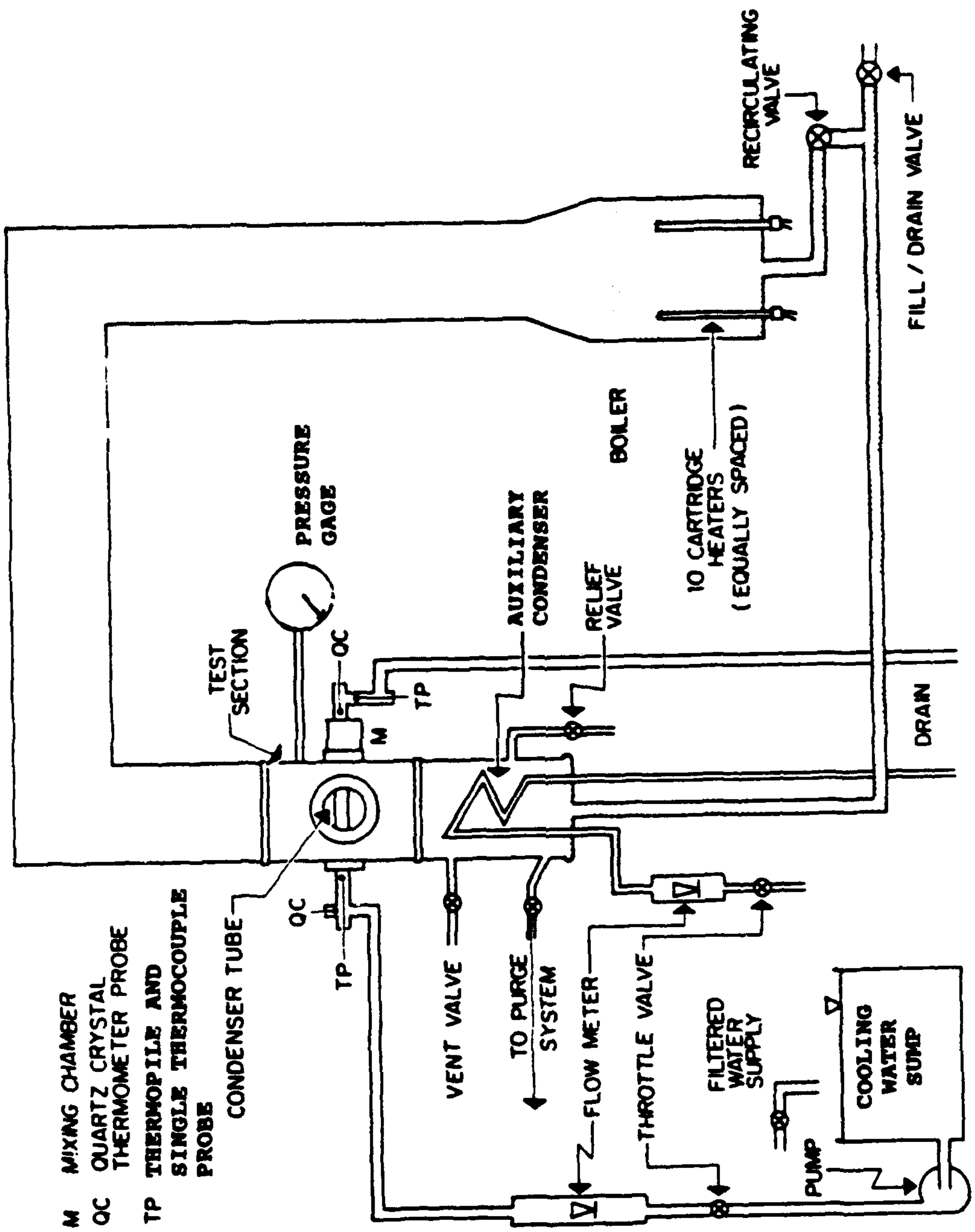

Figure 3.1 Schematic of the Single Tube Test Apparatus

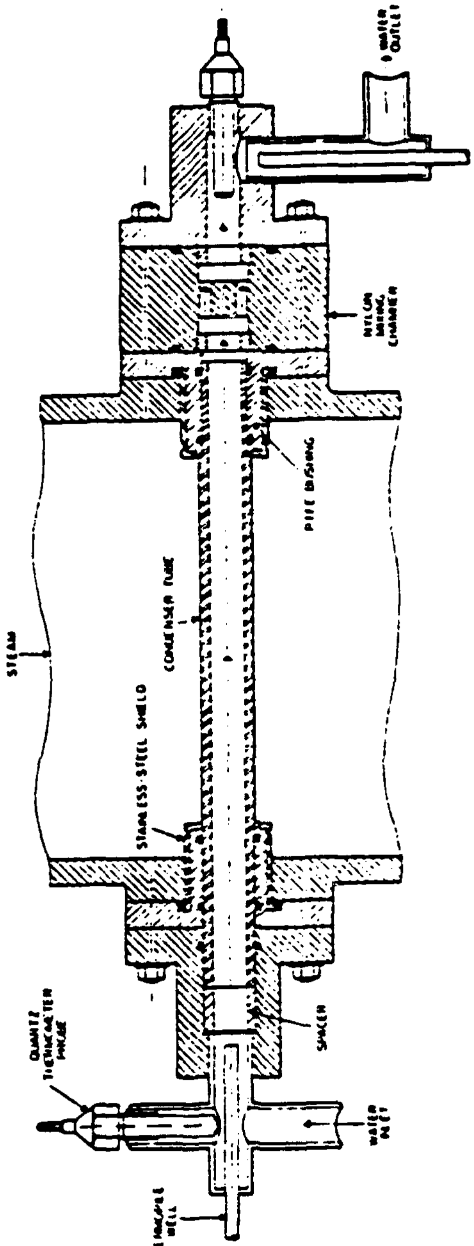

Figure 3.2 Schematic of the Test Section

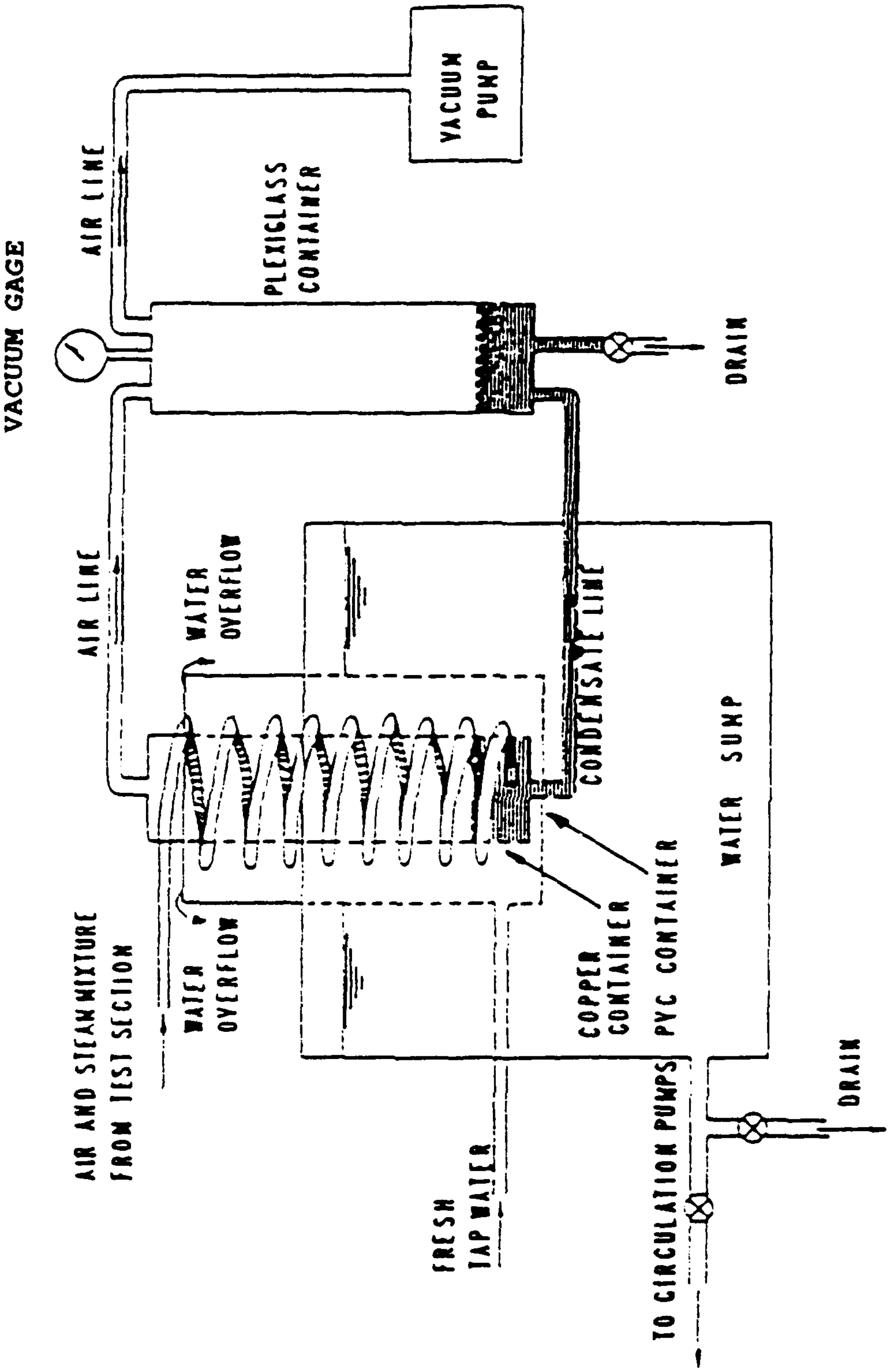

Figure 3.3 Schematic of the Purging System and Cooling Water Sump

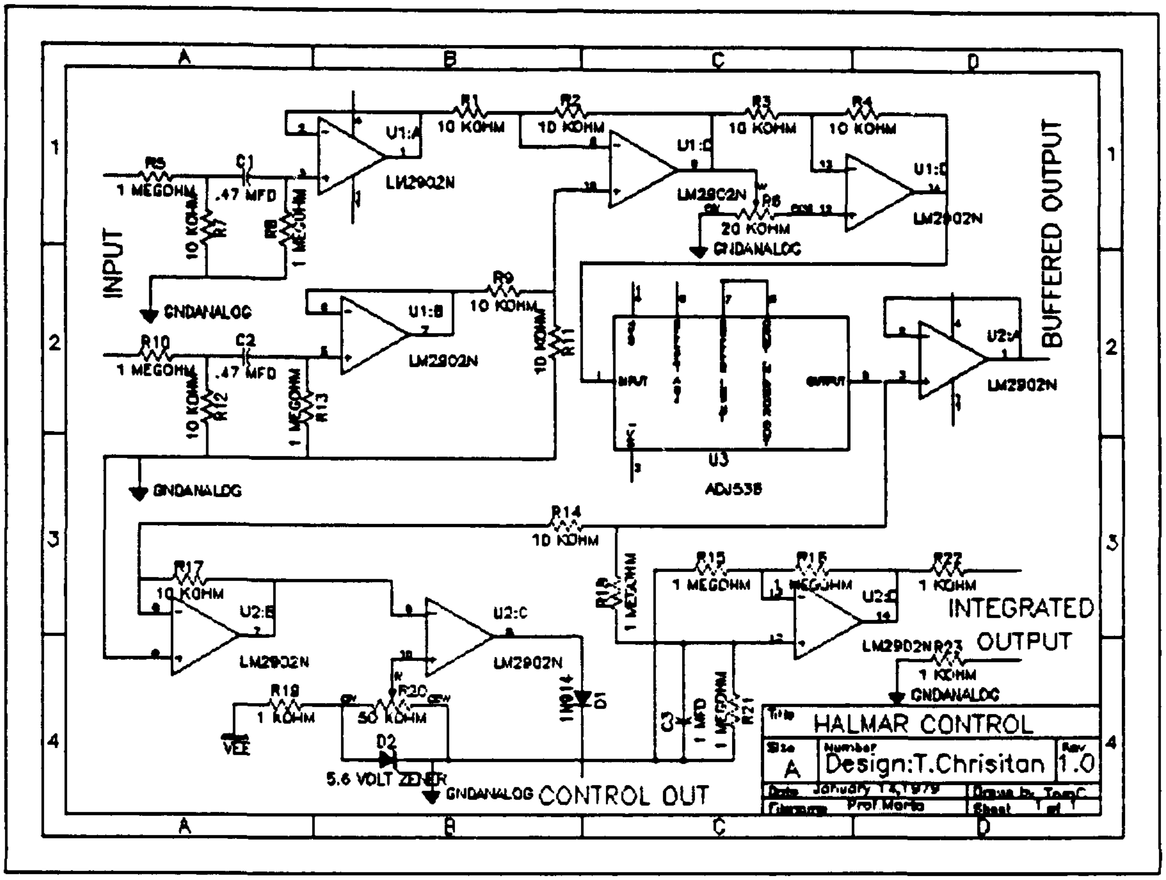

Figure 3.4 Single Line Wiring Diagram of the Controller Circuit for the emf Voltage Signal Input to the Data Acquisition Unit

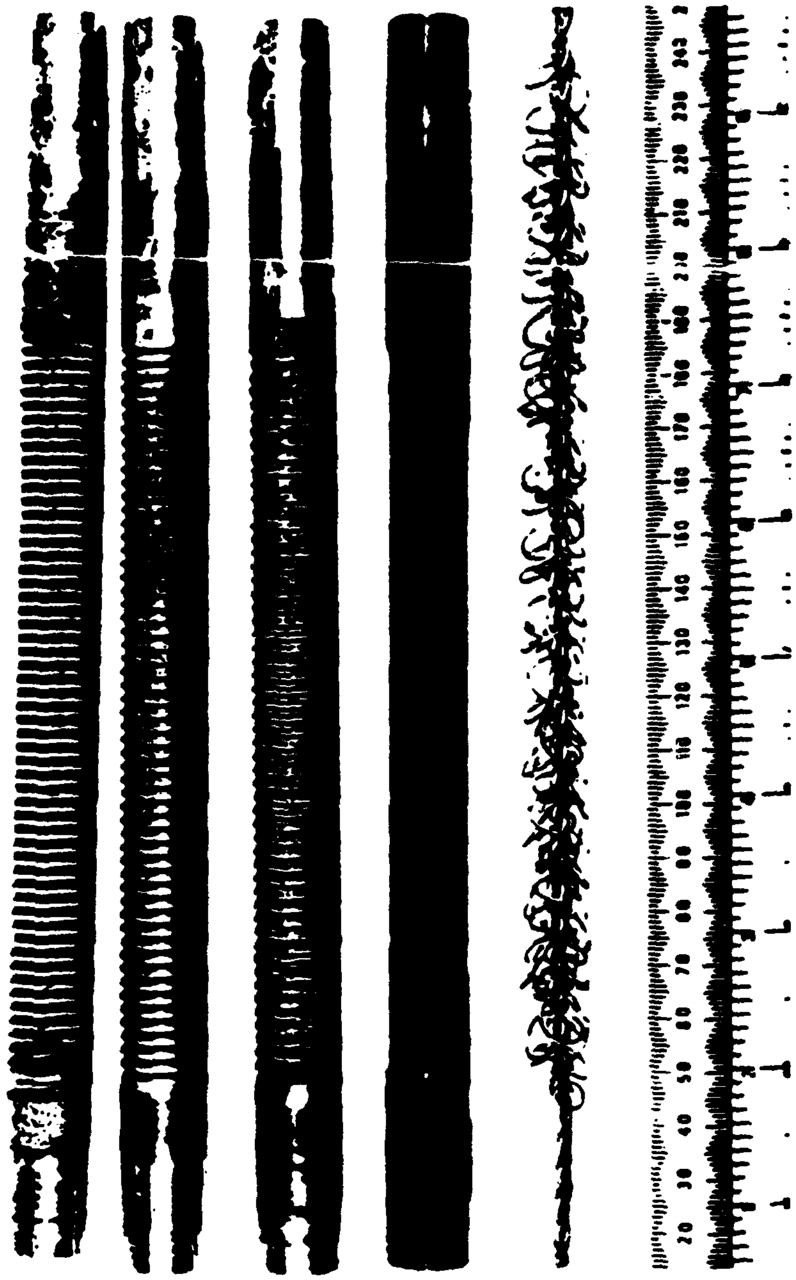

Figure 3.5 Photograph of the Four Types of Tubes Tested and Heatex Insert used (from left to right rectangular shaped finned tube, deep radiussed root finned tube, shallow radiussed root finned tube, smooth tube, and insert)

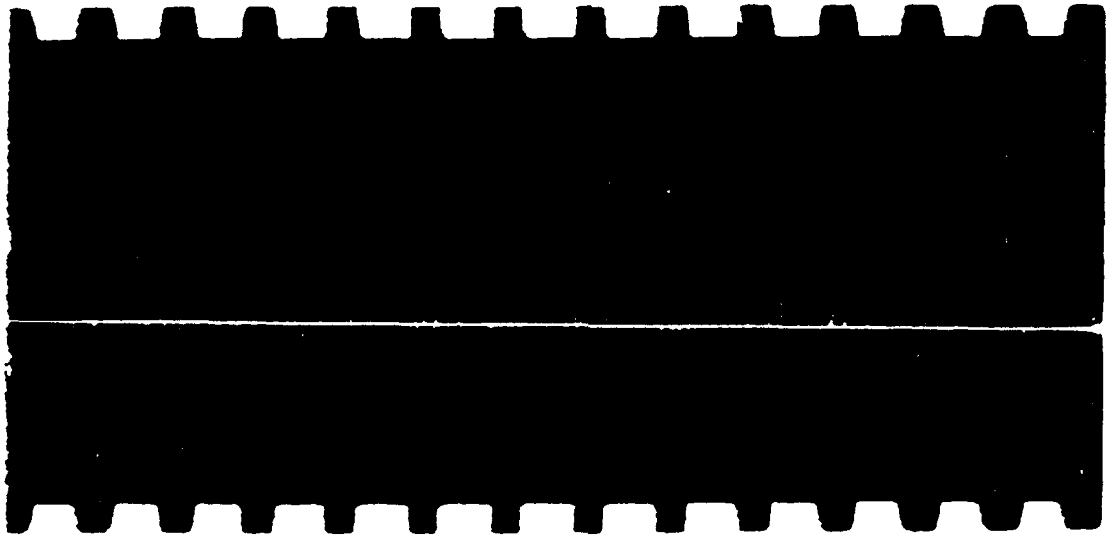

Figure 3.6 Photograph of the Rectangular Shaped Finned Tube

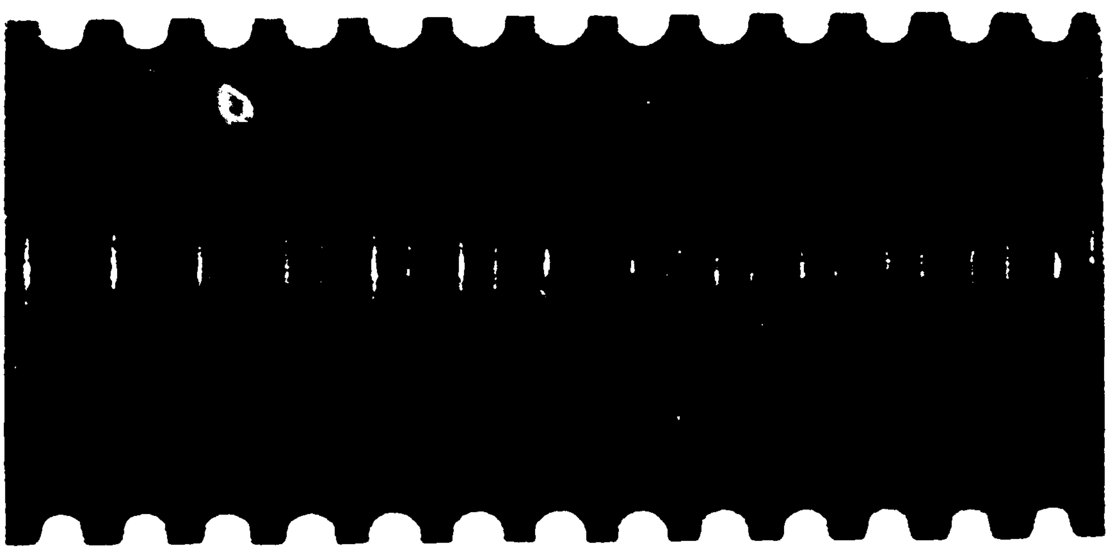

Figure 3.7 Photograph of the Deep Radiussed Root Finned Tube

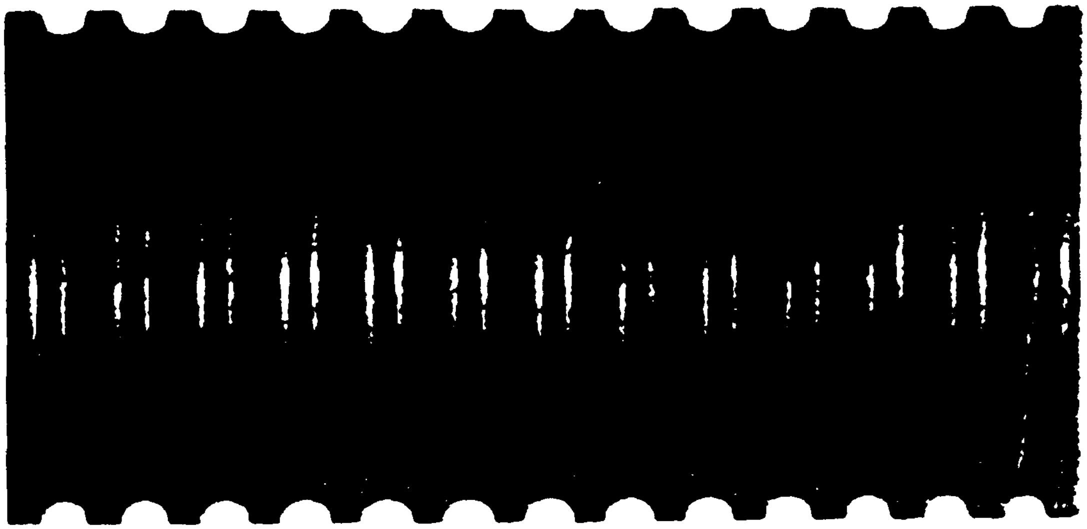

Figure 3.8 Photograph of the Shallow Radiussed Root Finned Tube

IV. EXPERIMENTAL PROCEDURES AND DATA ANALYSIS

A. TUBE PREPARATION

Prior to operation, the test tubes were cleaned and chemically treated to promote filmwise condensation during the data collection process. The chemical treatment solution [Ref. 30] had been used by several other researchers at NPS and was developed for copper tubes. The solution was a mixture of 50 percent by weight of sodium hydroxide and ethyl alcohol. This solution was modified during this thesis to 50 milliliters of ethyl alcohol combined with 1/2 teaspoon of sodium hydroxide pellets. The solution does not affect stainless steel but it is important to follow the same procedure for a completely uncontaminated tube. Additional chemical treatment solutions are contained in [Ref. 31]. Guttendorf [Ref. 13] outlined the basic procedure. The following procedure was used:

1. The outside of the tube was thoroughly cleaned with a mild soap solution using a soft bristle brush. A circular wire brush was used for the inside. The soap was rinsed off and the tube was checked for filmwise condensation. Breaks in the film indicated contamination and dropwise condensation. If there were signs of breakage, the outside surface was again cleaned with the soap solution and rinsed with distilled water. Once a continuous film was present, the active surface was not touched.

2. The tube was then placed in a steam bath, to heat the tube and surround the tube surface with moist air.

3. The sodium hydroxide and ethyl alcohol solution was then applied to the tube surface. The solution should be mixed prior to the each treatment because the sodium hydroxide absorbs CO^2 from the air which could affect the compound solution. It was kept warm (~25^{0}C) to ensure a watery consistency.

4. The solution was applied with a small brush in 10 minute intervals for one hour. While applying the solution, the tube was rotated to ensure the entire surface was treated. The wire brush handle was used to maintain the position of the tube over the steam bath. If the tube was treated previously, the tube was cleaned with the soap solution and rinsed with distilled water. If there were no film breaks, the tube was placed in the steam bath and the solution was applied every 5 minutes over a 20 minute period.

5. After the tube surface was treated, it was removed from the steam bath and rinsed with acetone to remove excess solution. The acetone was rinsed with distilled water. If there were no breaks in the film, the tube was inserted into the test section. After the insert was installed, coolant flow was started to the tube to maintain the film. A leak check of the cooling water system was performed and the flow rate was set at about 65%.

The oxide layer formed by the chemical treatment promoted a continuous film on the tube surface. The film was very thin, making the thermal resistance insignificant in the overall resistance of the tube.

B. SYSTEM START-UP AND SHUTDOWN PROCEDURES

Once the system was assembled, it could be brought on-line using the following procedures:

1. The boiler section must be filled with distilled water to a level approximately 4 to 6 inches above the top of the heater elements. If the test tube was not installed, the boiler was filled by gravity drain from the distilled water tank. This was done by attaching a hose to the drain/fill line below the boiler. To

reduce time, if the test tube was installed, the boiler was filled by vacuum drag. Vacuum drag was accomplished by placing the system under a vacuum (~10 psia), connecting the fill hose and then opening the drain/fill valve.

2. When the appropriate water level has been achieved, shut the fill/drain valve. The by-pass/condensate return valve was always left open. The by-pass/condensate valve is located below the boiler, between it and the condensate drain/fill valve.

3. Energize the data acquisition unit, computer, printer, and quartz thermometer power supplies. These units are normally left on line. Load the software program DRPALL and check for proper operation. To load the program, insert the program disk and type *LOAD "DRPALL"*. Type *RUN* and answer the prompt questions up to "ENTER FLOWMETER READING". The data acquisition unit should be displaying channel 40 in the remote setting. If the system power supplies are maintained from a previous run, this is not required. Verify that thermocouple outputs all correspond to ambient temperature.

4. Open the fill valve to the cooling water supply tank and adjust the flow. It needs only to be cracked open. The flow should be set low enough to ensure that the drain box to the bilge does not overflow. The fill valve is the valve located to the left of the boiler switchboard near the wall.

5. Perform a leak test on the water systems.

   a. Check the cooling system again for leaks.

   b. Open the water flow control valve to the auxiliary condenser and adjust the flow rate to at least 30% and check for leaks. If no leaks are present, reset the flow rate to at least 10%.

6. If the system was open to the atmosphere, place the system under a vacuum. To do this, shut the drain valve in the plexiglas container and energize the vacuum pump. After the pressure gage for the vacuum pump on the plexiglas container reaches 24 inches of vacuum, open the suction valve located on the side of the auxiliary condenser. If the pressure in the test apparatus does not drop below 8 psia, check the atmospheric valve to the auxiliary condenser and the vacuum drain valve below the plexiglas container and

ensure they are closed. After the pressure is below 3 psia, shut the vacuum suction valve and secure the vacuum pump.

7. To energize the heaters, three switches must be shifted "ON":

   a. Switch #3 on panel pnl 5 located on the right hand wall of the hallway to the machine shop.

   b. The heater load bank circuit breaker is on the left side of the electrical switchboard behind the HP computer desk.

   c. The condensing rig boiler power supply switch is on the front of the electrical switchboard.

The power supply in pnl 5 is left on. To start-up the boiler, flip the load bank circuit breaker to "ON". The voltmeter should indicate 100 volts. Ensure the resistance control knob is turned completely to the left. The control knob is located below and to the right of the voltmeter. Next, shift the boiler power supply switch on. The voltage indication should go to zero. If not, secure the switches and contact an electrical technician. Adjust the voltage to 50 volts using the control knob. If the system is below 2 psia, adjust the power level to 40 volts for initial start-up. The system is started at a low power level to minimize the vibrational shock to the system from vapor bubble formation and collapse. As the system warms up, the power can be increased, in increments of 10 volts, until the desired setting is reached.

8. After the system pressure rises above 4 psia, air and other non-condensible gases must be purged from the system. This is accomplished by following the procedures outlined in step 6. When the Pyrex glass

container around the auxiliary condenser is warm to the touch, most of the non-condensible gases have been removed. The purging procedure can not be done with both cooling water pumps on the line. The large power load will trip the power supply breaker in the panel outside the door to the lab. The initial purge takes about 15 - 20 minutes. The purging process should be repeated every few hours during extended operations.

9. The filmwise condensation established during the tube installation should still exist. If not, the following procedure must be followed to establish filmwise condensation:

   a. Secure cooling water to the tube and the auxiliary condenser. Allow the system vapor temperature to increase to at least 3800 microvolts, on channel 40.

   b. Increase the flow rate in the auxiliary condenser to 50% and allow the vapor temperature to decline to 3200 microvolts.

   c. Secure coolant flow to the auxiliary condenser and allow the vapor temperature to increase to about 3700 microvolts. This forms a steam blanket over the tube.

   d. Initiate cooling water flow to the horizontal tube at a flow rate of 80%.

   e. Start the flow to the auxiliary condenser at maximum. Adjust the flow rate to maintain desired pressure and temperature.

If, after performing these steps, some dropwise condensation persists, repeat step (9) again. If dropwise condensation continues, the tube should be removed, cleaned and retreated. Notes should be made of locations of machine tool marks. They can give the appearance of dropwise condensation if they are retaining condensate.

10. Press the "RUN" key on the keyboard to activate the DRPALL program. The program will prompt you with questions for the necessary data information. A copy

of the data collection program is listed in Appendix A.

11. Ensure the system has been operating at steady state condition for at least 30 minutes prior to continuing past the statement "ENTER FLOWMETER READING". Several variables must be monitored at the same time. Each operator must obtain a feel for the equipment to determine a steady state condition. The pressure input into the program is only a visual reference and is not used in the program calculations. A steady state condition is defined as a good agreement in the following printouts: pressure (Ptran,Psat), temperature differential (quartz,T-pile, thermocouple) and the overall heat transfer coefficient (U_0) from the previous data run printout. The difference between the pressure readings for the transducer and the voltage conversion should be less than 0.5 kPa and 0.1 kPa from the previous run. The three temperature differentials should be within .01^{0}C of the previous run and within .05^{0}C of each other. The overall heat transfer coefficient should be within 100 (W/(m^{2}K)) of the previous data run.

12. For vacuum runs, the control setting on the voltmeter is 90 volts. Channel 40 on the data acquisition system should be 1980 $\pm$ 10 microvolts. This corresponds to T_{sat} $\approx$ 48^{0}C, and a vapor velocity of $\approx$ 2 m/s.

13. For atmospheric runs, the control setting on the voltmeter is 175 volts and channel 40 on the data acquisition system is 4280 $\pm$ 10 microvolts. This corresponds to T_{sat} $\approx$ 100^{0}C, and a vapor velocity of $\approx$ 1 m/s. Special care must be used when operating at atmospheric pressure to ensure overpressurization and rupture does not occur.

14. If both vacuum and atmospheric runs are to be conducted on the same day, the vacuum run should be conducted first. This eliminates the long cool down time required after an atmospheric pressure run.

The system should be secured using the following procedures:

1. Secure power to the heating elements. Turn the voltage control knob completely to the left. The voltage

indication on the voltmeter should be zero. Shift the boiler supply power switch to "OFF". The voltage indication on the voltmeter should rise to 100 volts. Press the power supply breaker to "OFF" and reinstall the safety bar.

2. Secure coolant flow to the auxiliary condenser. If the system is to remain at vacuum pressure until the next data run, then the auxiliary condenser can be used in assisting to cool the system down, provided the same tube will be used for testing.

3. Secure the coolant flow to the tube by shutting the inlet valve and securing the coolant pumps.

4. Secure the water flow to the coolant water sump tank.

5. Return the system to atmospheric pressure unless a system pressure leakage test is being performed. Open the vent valve on the auxiliary condenser slowly. Keep all foreign material away from the vicinity to avoid contaminating the system.

6. In case of any abnormal conditions or an emergency, **SECURE THE BOILER POWER FIRST.**

C. DATA PROGRAMS

The computer programs DRPALL and HEATCOBB were used to collect, store, and process the test data for analysis. DRPALL, a revision of the basic HP program, calculated and stored the raw data. HEATCOBB, a FORTRAN program, was written to reprocess the raw data for theoretical model comparison.

The DRPALL program used a series of internal program functions to convert voltage inputs from the data acquisition unit and the quartz thermometer into raw data. Raw data were calculated from both direct and indirect measured values. The overall thermal resistance for the heat transfer from the vapor to the cooling water is the sum of the vapor side (R_o),

the tube wall (R_w), and the coolant side (R_i) resistances. Since the tubes were cleaned prior to testing, the fouling resistance was negligible, (R_f ~ 0). The total resistance can therefore be represented as equation (4.1):

$$R_{total}=R_i+R_w+R_o \tag{4.1}$$

where,

$$R_i=\frac{1}{h_iA_i} \tag{4.2}$$

$$R_o=\frac{1}{h_oA_o} \tag{4.3}$$

$$R_w=\frac{\ln\left(\frac{D_o}{D_i}\right)}{2\pi Lk_c} \tag{4.4}$$

The effective area for the inside of the tube represents the entire length of the tube. The portions of the tube that do not contain fins were used to support the tube and act as fins extended in the axial direction. They transfer additional heat to the inlet and outlet portion of the tube. The effective inside surface area is represented as:

$$A_i = \pi D_i (L + L_1\eta_1 + L_2\eta_2) \tag{4.5}$$

The fin efficiencies (η_1 and η_2) for their respective entrance lengths are:

$$\eta_1 = \frac{\tanh(m_1 L_1)}{m_1 L_1} \tag{4.6a}$$

$$\eta_2 = \frac{\tanh(m_2 L_2)}{m_2 L_2} \tag{4.6b}$$

where,

$$m_1 = \left(\frac{hP_1}{k_c A_1}\right)^{1/2} \tag{4.7a}$$

$$m_2 = \left(\frac{hP_2}{k_c A_2}\right)^{1/2} \tag{4.7b}$$

P_1 and P_2 are the fin perimeters and A_1 and A_2 are respective the cross sectional areas. The actual outside surface area, the tube length exposed to steam, varies with each machined spacing between each fin. Therefore the effective outside area was assumed to be:

$$A_o = \pi D_r L \tag{4.8}$$

The overall thermal resistance can be related to the overall heat transfer coefficient (U_o) and the effective outside area (A_o) by:

$$R_{total} = \frac{1}{U_o A_o} \tag{4.9}$$

Substituting equations (4.2), (4.3), and (4.9) into equation (4.1) gives:

$$\frac{1}{U_o A_o} = \frac{1}{h_i A_i} + R_w + \frac{1}{h_o A_o} \tag{4.10}$$

The heat transfer rate, Q, can be calculated from the measured inlet and outlet temperatures and the mass flow rate of the cooling water through the test tube.

$$Q = \dot{m} c_p (T_2 - T_1) \tag{4.11}$$

Using the energy balance for a control volume, the heat transfer rate can be expressed in terms of the overall heat transfer coefficient (U_o):

$$Q = U_o A_o (LMTD) \tag{4.12}$$

where the log mean temperature difference, LMTD, is:

$$LMTD=\frac{T_2-T_1}{\ln\left[\frac{T_{sat}-T_1}{T_{sat}-T_2}\right]} \tag{4.13}$$

The inlet (T_1) and outlet (T_2) cooling water temperatures were measured directly with the quartz thermometer and the saturation temperature (T_{sat}) was measured using the vapor thermocouple (channel 40) from the data acquisition unit. The specific heat of the coolant at constant pressure (c_p) was determined from the bulk mean temperature of the cooling water. In addition, a correction factor was used to account for the viscous heating of the coolant through the test tube with a heatex insert; the correction equations are located in Appendix B.

Once the total heat transfer rate has been calculated, the overall heat transfer coefficient can be calculated by using equation (4.12). The only two unknowns, the inside heat transfer coefficient (h_i) and outside heat transfer coefficient (h_o), are computed using the Modified Wilson Plot Technique.

The Modified Wilson Plot Technique uses the overall heat transfer coefficient determined from the experimental data to determine the inside and outside heat transf^r coefficients. The technique uses an assumed leading coefficient for the

inside and outside heat transfer coefficients and iterates to determine the unknown heat transfer coefficients. Briggs and Young [Ref. 32] explain this technique in detail. The two forms of the equations used are:

For the outside heat transfer coefficient,

$$h_o=\alpha\left[\frac{k_f^3\rho_f^2 g h_{fg}}{\mu_f D_r \Delta T_f}\right]^{1/4}=\alpha Z \tag{4.14}$$

where α is a dimensionless Nusselt coefficient [Ref. 16].

For the inside heat transfer coefficient,

$$h_i=C_i\left(\frac{k_{cw}}{D_i}\right)\Omega \tag{4.15}$$

All data were taken using the Petukhov-Popov correlation [Ref. 33] for the inside heat transfer coefficient. Therefore,

$$\Omega=\left[\frac{\left(\frac{\epsilon}{8}\right)RePr}{K_1+K_2\left(\frac{\epsilon}{8}\right)^{1/2}(Pr^{2/3}-1)}\right] \tag{4.16}$$

where:

$$\epsilon=[1.82\log(Re)-1.64]^{1/2} \tag{4.17}$$

$$K_1 = 1 + 3.4\epsilon \tag{4.18}$$

$$K_2 = 11.7 + 1.8 Pr^{-1/3} \tag{4.19}$$

Substituting equations (4.14) and (4.15) into equation (4.10) and rearranging the terms gives:

$$\left[\frac{1}{U_o} - R_w A_o\right] Z = \frac{A_o Z D_i}{C_i \Omega A_i k_{cw}} + \frac{1}{\alpha} \tag{4.20}$$

Letting:

$$Y = \left[\frac{1}{U_o} - R_w A_o\right] Z \tag{4.21}$$

$$X = \frac{A_o Z D_i}{A_i \Omega k_{cw}} \tag{4.22}$$

$$m = \frac{1}{C_i} \tag{4.23}$$

and

$$b = \frac{1}{\alpha} \tag{4.24}$$

resulted in a simple linear equation:

$$Y=mX+b \tag{4.25}$$

The parameters Ω and Z are temperature dependent, so an iterative procedure must be used to solve the equations. A least squares fit of equation (4.25) was used to determine C_i and α. The inside heat coefficient could now be determined from equations (4.15) and (4.16). With the inside heat transfer coefficient and the overall heat transfer coefficient determined, the outside heat transfer coefficient can be solved using equation (4.10).

The conditions for a data run cannot be exactly reproduced, resulting in a variation between C_i and α values between runs for the same tube.

From Nusselt theory, the heat flux (q) based on the outside area can be shown as:

$$q=a\Delta T_f^{3/4} \tag{4.26}$$

where:

$$a=\alpha\left[\frac{k_f^3\rho_f^2 g h_{fg}}{\mu_f D_r}\right]^{1/4} \tag{4.27}$$

and

$$q=h_o \Delta T_f \tag{4.28}$$

where:

$$h_o=a\Delta T_f^{-1/4} \tag{4.29}$$

The enhancement ratio based on a constant temperature drop across the condensate film, can be expressed as:

$$\varepsilon_{\Delta T}=\frac{h_{of}}{h_{os}}=\frac{a_f}{a_s}=\frac{\alpha_f}{\alpha_s} \tag{4.30}$$

The enhancement ratio for constant (ΔT) can be defined as the improvement in the heat transfer rate of a finned tube compared to the heat transfer rate of a smooth tube with an outside diameter equal to the root diameter of the finned tube for the same temperature difference.

The Fortran program, HEATCOBB listed in Appendix C, used the experimental values for the vapor, condensate film, and the differential temperatures to solve for an outside heat transfer coefficient. The outside heat transfer coefficient determined from equation (1.1), the Beatty and Katz correlation, was obtained by iterating the fin efficiency for the material and assuming an initial outside heat transfer coefficient. This heat transfer coefficient used the effective area of the fin A_{ef} so that a correction factor must

be applied to it the heat transfer coefficient in order to compare it with the outside heat transfer coefficient obtained during this thesis. The correction factor was the ratio of the effective area divided by the area of a smooth tube having a diameter equal to the root diameter of the finned tube. The heat transfer rate Q, can be expressed as follows:

$$Q=h_{ef}A_{ef}\Delta T \tag{4.31}$$

where h_{ef} and A_{ef} were determined from equations (1.1) and (1.4), respectively; or in terms of the outside area A_o:

$$Q=h_oA_o\Delta T. \tag{4.32}$$

By substituting and rearranging equations (4.31) and (4.32), the outside heat transfer coefficient using the Beatty and Katz correlation was modified to get:

$$h_{BK}=h_{ef}\frac{A_{ef}}{A_o}. \tag{4.33}$$

During this thesis, the enhancement ratio was defined by dividing the outside heat transfer coefficient for the finned tube by the outside heat transfer coefficient for a smooth tube from Nusselt theory as:

$$\acute{\epsilon}_{\Delta T}=\frac{h_{BK}}{h_{Nuss}} \tag{4.34}$$

As shown in Chapter II, the efficiency of a fin, equation (2.7), changes with the fin profile area A_p. For this thesis, the profile area for a radiussed root finned tube was calculated from equation (4.35):

$$A_p = \left(\frac{t}{2}+h\right)(s+t) - s\left[\left(R_2-\left(R_1+\frac{s}{2}\right)\right)+\frac{t}{2}\right] - \frac{\pi}{2}\left(\frac{s}{2}\right)^2 \qquad (4.35)$$

and the fin efficiency was determined by substituting this profile area into equation (2.8). The total surface area of a radiussed root finned tube decreases compared to a rectangular shaped finned tube but the profile area increases. This increase in profile area decreases the value of ξ in equation (2.8), and as seen in Figure (2.2), the fin efficiency will increase.

Also in the Fortran program, HEATCOBB, the basic enhancement ratio for constant (ΔT) as proposed by Rose [Ref. 8], equation (2.36), was modified. The fin efficiency determined in the Beatty and Katz model was applied to the unblanked surfaces of the fin. The enhancement ratio for a rectangular shaped finned tube becomes:

$$\epsilon_{\Delta T} = \frac{h_{ROSE}}{h_{NUSS}} = \frac{D_o}{D_r}\frac{t}{(s+t)}T_t\eta + \frac{\Phi}{\pi}(1-f_f)\left[\frac{D_o^2-D_r^2}{2D_r(s+t)}\right]T_f\eta + \frac{\Phi}{\pi}(1-f_s)B_1\frac{s}{(s+t)}T_s \qquad (4.36)$$

Unlike a rectangular shaped finned tube, in the case of a radiussed root finned tube, the unflooded (ie, the region from the top of the tube to a point where the whole of the flank is just wetted and where the condensate film at the center of the interfin space has a finite thickness) surface areas of the fin flank and the radiussed root do not have any condensate "wedge" blanking them off. The condensate flooding angle ϕ was still calculated from equation (1.8) and the estimated fraction of the fin flanks and radiussed interfin space blanked by condensate, f_f and f_s, was set equal to zero. The enhancement ratio for a radiussed root finned tube becomes equation (2.20):

$$\varepsilon_{\Delta T}=Q_f/Q_s$$

where the numerator is:

$$Q_f=2\pi r_2 t q_t \eta+\left(\frac{\phi}{\pi}\right)\left[2\pi\left(r_2^2-\left(r_1+\frac{s}{2}\right)^2\right)q_f\eta+2\pi\frac{s}{2}B_1\left(r_1+\frac{s}{2}\left(1-\frac{2}{\pi}\right)\right)q_s\eta\right] \tag{4.37}$$

and the denominator is given by equation (2.22). In equation (4.37), the heat flux for the interfin space was varied from equation (2.25) to account for the changing geometry along the radiussed root:

$$q_s=\left[\frac{\rho h_{fg}k^3\Delta T^3}{\mu}\left[\frac{(\xi(\phi))^3\tilde{\rho}g}{(D_r+s(1-(2/\pi))}+\frac{B_s\sigma}{s^3}\right]\right]^{1/4} \tag{4.38}$$

As mentioned in Chapter II, the Rose [Ref. 8] model required that the constants B_1, B_f, B_s, and B_t be specified. The value of all these constants will vary with the tube material and fin geometry. They cannot be determined accurately until more data is obtained for a variety of radiussed root finned tubes. This thesis therefore used the B-values determined by Rose [Ref. 8]. The heat flux for the fin tip was still defined as in equation (2.27) and for the fin flanks equation (2.24) was used. However, the fin height was modified as noted below:

$$h=R_2-\left(R_1+\frac{s}{2}\right). \qquad (4.39)$$

Using equations (4.37), (4.38) and (4.39), equation (2.20) can be used to find the enhancement ratio, $\epsilon_{\Delta T}$ for a radiussed root finned tube.

V. RESULTS AND DISCUSSION

A. GENERAL DISCUSSION

Experimental data were taken as described in Chapter IV. A short format version of the data printout for the tubes tested is contained in Appendix D. The tube numbers are listed in TABLE II in Chapter III along with their respective geometries. Nomenclature for the data runs are as follows. The first two letters are the run condition, i.e. AT for atmospheric and VT for vacuum condition; the two numbers or group of letters are the tube number from TABLE II; and, the last number is the run number. For example, the nomenclature "VT094" means that this is the fourth data run for tube number 9, a rectangular shaped finned tube made of stainless steel(316), under vacuum condition.

The cooling water flow rate settings for atmospheric condition data runs were from 80 to 20 percent of the rotameter scale in increments of 10 percent; the procedure was then reversed back to 80 percent. This procedure could not be followed for the vacuum runs because of the inability to maintain the required temperature and pressure setting for a complete data set. The problem maintaining the set points was attributed to the long settling time between data points and

the cooling effects of the environment surrounding the test apparatus. In the early data sets, it took about 45 minutes to reach a steady state condition described in Chapter IV. This resulted in a 13 to 15 hour data taking session. Several attempts were made to reduce the run time. One attempt was to secure the augmenting tap water to the cooling water sump for the test tube. Increasing the temperature of the cooling water flowing through the test tube reduced the temperature difference across the test tube and the amount of steam condensed by the test tube. This increased the amount of steam to be condensed by the auxiliary condenser and increased the control of the temperature and pressure settings. However, this reduced the range of the temperature difference for the data obtained. The other attempt was to change the sequence of the data by changing the cooling water flow rate through the test tube. The sequence was changed to 80 , 20, 70 , 30, 60, 40, 50 (2), 40, 60, 30, 70, 20 and then back to 80 percent instead of the procedure as described for the atmospheric conditions. The data obtained from this procedure where compared to previous runs for consistency and repeatability. There were no noticeable variations; thus, this procedure was used for the remaining vacuum data runs.

The condensate film was checked as described in Chapter IV. During the purging operations, the condensate film was re-verified and the data collection process continued if the condensate film was intact. The revised chemical treatment

solution, as stated in Chapter IV, produced filmwise condensation on the same tubes weeks after testing.

Great care and attention to detail were taken to obtain good reliable data. With all experiments, everything cannot be accounted for, leading to uncertainties in the measurements. The uncertainty calculations obtained for randomly chosen data points are contained in Appendix E and do not account for air and other non-condensible gases or possible dropwise condensation conditions over any portion of the test tube.

B. SMOOTH TUBE RESULTS

The overall heat transfer coefficient for a given outside diameter depends on the tube material. Equations (4.1) and (4.9) relate the overall heat transfer coefficient to the total resistance. As the wall resistance decreases, the overall heat transfer coefficient increases. Figures 5.1 and 5.2 show the overall heat transfer coefficient versus velocity behavior for copper tubes under atmospheric and vacuum conditions, respectively. Two tubes were used, with slightly different diameters. Thus the wall resistance (R_w) was about the same for each tube. Using a Heatex insert improved the accuracy of the data taken by reducing the influence of the inside resistance (R_i) on the overall heat transfer coefficient. The data show that the outside resistance (R_o) must dominate the overall heat transfer resistance since, as

cooling water velocity increases, the overall coefficient remains constant. In addition, the results appear to be independent of operating pressure.

Comparing Figures 5.1 and 5.3 for runs ATSMTH1 and ATSMTH3 which had the same outside diameter tube (D_r=14.38mm), the outside heat transfer coefficient (h_o) is nearly constant over the range of temperature differences (Ts-Tw). The corresponding overall heat transfer coefficients in Figure 5.1 change very slightly, again indicating that the outside resistance is the controlling resistance.

From Nusselt theory, the outside heat transfer coefficient is independent of tube material. Experimentally obtained smooth tube data were compared to the data of Guttendorf [Ref. 13] who used a copper tube and Long [Ref. 34] who used titanium. It appears that the Guttendorf data is high (about 14%) and the Long data is low (about 4%). This is due partially to the different diameters used. Since the Nusselt theory predicts that the outside heat transfer coefficient, h_o, is proportional to $D_o^{-1/4}$, then the diameters will influence the measured result. In addition, Guttendorf used a twisted tape insert (i.e., a small rectangular shaped wire twisted around a metal rod in a spiral manner) vice a wire mesh insert as used in this thesis. A similar comparison was made for vacuum conditions. Since the outside heat transfer coefficient for a smooth tube is independent of wall material,

all finned tube data were compared to the smooth tube data taken for the copper tube.

C. RECTANGULAR SHAPED FINNED TUBE RESULTS

Figure 5.4 shows the data of the overall heat transfer coefficient (U_o) versus cooling water velocity (Vw) for rectangular shaped finned tubes of copper, aluminum, copper nickel, and stainless steel at atmospheric conditions. In addition, smooth tube data for copper and titanium are provided for comparison.

Comparing the four rectangular shaped finned tubes, as the thermal conductivity (k_c) increases, the overall heat transfer coefficient increases. At a cooling water velocity of 3.5 m/s, the ratio of the overall heat transfer coefficient for copper to stainless steel ($U_o(Cu)/U_o(SS)$) is 2.6. Since the dimensions of these tubes are the same, this significant enhancement is due to 1) a smaller wall resistance to base of the fins for copper and 2) a smaller wall resistance of the fins themselves. Both effects combine to determine the inside heat flux.

For low thermal conductivity material (i.e., stainless steel), the overall heat transfer coefficient is roughly constant for changing velocities. This indicates that the outside resistance (R_o) is controlling the overall heat transfer coefficient. As the thermal conductivity increases, the overall heat transfer coefficient increases with cooling

water velocity, implying that the outside resistance is not controlling the overall heat transfer coefficient as much (i.e., the inside resistance (R_i) is also important).

The heat transfer enhancement of the finned tube increases with the thermal conductivity of the tube material. Comparing the overall heat transfer coefficient of the copper finned tube to the copper smooth tube, the heat transfer enhancement for the 3.5 m/s cooling water velocity is 2.3. The enhancement at the same cooling water velocity for stainless steel is only 1.3 (since the thermal conductivity for stainless steel is about the same as titanium, the titanium smooth tube data of Long (D_r=15.85mm)was used). It is clear that for higher thermal conductivity materials, fins help considerably to improve the performance of the tube, but for lower thermal conductivity materials there is a small influence. Similar (but reduced) trends exist under vacuum conditions as shown in Figure 5.5.

The data obtained during this thesis for copper rectangular shaped finned tubes are compared to previous data in Figures 5.6 and 5.7, for atmospheric and vacuum conditions respectively. Flook [Ref. 35] tested a finned tube with the same dimensions as used in this thesis except it had a root diameter, D_r, of 13.7mm. He used a twisted tape insert along with the Seider-Tate [Ref. 36] correlation for the inside heat transfer coefficient, h_i, to obtain his data. The Seider-Tate [Ref. 36] relationship is:

$$h_i = C_i \frac{k_c}{D_i} Re^{0.8} Pr^{0.333} \left(\frac{\mu}{\mu_{cw}}\right)^{0.14}. \qquad (5.1)$$

When this correlation was compared to the Petukhov-Popov correlation by Incropera and Dewitt [Ref. 15], the Petukhov-Popov correlation was found to be the most accurate. Therefore, the Guttendorf [Ref. 13] and Van Petten [Ref. 12] raw data were reprocessed using the Petukhov-Popov [Ref. 32] inside heat transfer correlation. Guttendorf and Van Petten tested tubes with an inside diameter, D_i, of 9.53mm and root diameter, D_r, of 12.7mm. The fin height, spacing and thickness were the same as the rectangular shaped finned tubes used in this thesis. They also used the twisted tape insert which was described earlier. As plotted in Figures 5.6 and 5.7, the data obtained during this thesis fell between the data of the previous researchers. With the different tube diameters and inserts used, little additional comparison can be made. The Flook data could be erroneously high since his data were taken after Holden [Ref. 37] completed his thesis on the use of an organic coating to promote dropwise condensation of steam on horizontal tubes in the test apparatus. Some of the dropwise promoter may have been retained in the test apparatus during the measurements of Flook, causing dropwise condensation on the test tube vice filmwise. The data of Guttendorf and Van Petten were also obtained after Holden.

The actual reason for the variation in data is not known. The data obtained in this thesis could be low because of the presence of air and other non-condensible gases. However, care was taken to remove these gases. All the data are within an uncertainty of ± 20% for the same tube geometry and tube-side insert. Additional data should be taken with the same geometry and inserts to establish more accurate trends for comparison.

Mitrou [Ref. 14] tested rectangular shaped finned tubes of aluminum and copper nickel. Like Flook [Ref. 35], he also followed Holden [Ref. 37] in conducting his studies in the test apparatus. Since these earlier thesis studies, Swensen [Ref. 10] modified, disassembled, and cleaned the test apparatus to improve the accuracy of the data taken. Mitrou's fin dimensions were identical to Flook's copper tube. Mitrou's data were also reprocessed during this thesis using the Petukhov-Popov inside heat transfer coefficient correlation, but he used the twisted tape insert. Mitrou's data for aluminum and copper nickel finned tubes at atmospheric conditions are plotted in Figures 5.8 and 5.9 respectively. Similar to Flook's data, the Mitrou results are higher than those found in this thesis. It is obvious from these figures that, although the exact magnitude for a given material may be uncertain, the outside heat transfer coefficient is influenced by the thermal conductivity of the

tube material. This pattern holds for vacuum conditions also, as shown in Figure 5.10.

Figure 5.11 summarizes the experimentally obtained outside heat transfer coefficient data versus the temperature difference between the vapor and the outer tube wall (Ts-Tw). The outside heat transfer coefficient increases as the thermal conductivity of the finned tube material increases, implying that it is not desirable to fin a low conductivity tube. As discussed earlier for the overall heat transfer coefficient results, this is due to 1) the wall resistance to the fin base and 2) the wall resistance of the fin itself. This trend can also be seen by overlapping the data in Figures 5.6, 5.8, and 5.9.

D. RADIUSSED ROOT FINNED TUBE RESULTS

Radiussing the root of the rectangular shaped finned tube is designed to remove retained condensate from the unflooded part of the tube, thus improving the thermal performance of the tube. Figure 5.12 compares overall heat transfer coefficient data of rectangular shaped finned tubes to radiussed root finned tubes for the four materials studied in this thesis at atmospheric conditions. In all cases, except for stainless steel, radiussing the base root reduced the finned tube performance of the materials tested. Because of the poor thermal conductivity of stainless steel, the increased fin profile area by radiussing the root had a

greater impact on the fin efficiency than for the higher thermal conductivity materials. The dispersion in the overall heat transfer coefficient data was greater for the highest thermal conductivity material (copper) and decreased with thermal conductivity.

Figures 5.13 and 5.14 show the outside heat transfer coefficient versus the temperature difference between the vapor and the outer wall (Ts-Tw) at atmospheric conditions. Data were obtained for all four materials as well as for deep and shallow radiussed root finned tubes. Figure 5.13 shows the data for the deep radiussed root tubes whereas the shallow radiussed root tubes data are shown in Figure 5.14. In both figures, the influence of the thermal conductivity of the tube material can be seen. As the thermal conductivity of the tube material increases, the outside heat transfer coefficient increases. This increase in the heat transfer coefficient is somewhat sensitive to the finned tube geometry, as can be seen when comparing the two figures.

Figures 5.15 and 5.16 display the data for the three types of finned tube geometries used during this thesis. Two tube materials are shown in each figure. Figure 5.15 contains copper and copper nickel outside heat transfer coefficient data whereas Figure 5.16 shows the data for aluminum and stainless steel. For the higher thermal conductivity (copper) material, the data were higher than the lower thermal conductivity (copper nickel) material for all geometries. For

both materials, the outside heat transfer coefficient decreased in going from a rectangular shaped finned tube to a radiussed root finned tube. The root diameter of the shallow radiussed root finned tube (D_r= 14.38mm) is larger than the root diameter (D_r= 13.88mm) of the deep radiussed root and rectangular shaped finned tubes. For the higher thermal conductivity materials, (i.e., copper and aluminum) the outside heat transfer coefficient for the shallow radiussed root finned was lower than the deep radiussed root finned tubes. In Figure 5.15 for copper nickel, no conclusions can be drawn between the outside heat transfer coefficient for the radiussed root finned tubes. For stainless steel which has the lowest thermal conductivity, the data in Figure 5.16 show that the outside heat transfer coefficient appears to be the same regardless of the external fin geometry.

E. HEAT TRANSFER ENHANCEMENT

As described earlier in Chapter IV, the modified Wilson Plot procedure curve fits the raw data to determine a leading coefficient (C_i) and an alpha (α) value for the inside and outside coefficients, respectively. TABLES III and IV contain the averaged leading coefficients and alpha values obtained for each tube tested for atmospheric and vacuum conditions, respectively. The leading coefficients and alpha values changed with each material, but no particular pattern or trend can be established. For example, for the rectangular shaped

finned tubes, as the tube material changes from copper to stainless steel, the leading coefficient for the inside heat transfer coefficient (Ci) changes from 3.11 to 2.10. This implies that circumferential wall conduction may be important in establishing the heat flux around the tube. Additional runs with smooth tubes having wall thermocouples are required to study the effect of the tube wall material on the leading coefficient and alpha values.

An alternate method to study the experimentally obtained enhancement is to compare the outside heat transfer coefficients obtained at the same temperature difference (ΔT). The outside heat transfer coefficient data at a temperature difference of 30°K for atmospheric conditions and 12°K for vacuum conditions are listed in TABLES V and VI. The enhancement ratio for atmospheric conditions for the four tube materials and various finned tube geometries are tabulated in TABLE VII using the smooth tube outside heat transfer coefficient as the baseline. TABLE VIII provides similar ratios using Nusselt theory as the baseline. In both tables, the enhancement ratio decreases as the thermal conductivity of the tube wall material decreases. By radiussing the fin root, the enhancement ratio decreases except for stainless steel. TABLES IX and X contain similar enhancement ratios for the four materials under vacuum conditions. Similar trends are evident.

The experimentally obtained film temperature differences were used to obtain enhancement ratios from the empirical models of Beatty and Katz [Ref. 1] and Rose [Ref. 8] for rectangular shaped finned tubes. Figure 5.17 presents the predicted enhancement ratios for the Beatty and Katz model, equation (4.34), and the modified Rose model, equation (4.36), versus the change in fin spacing for copper, aluminum, copper nickel, and stainless steel tubes under atmospheric conditions. Figure 5.17 also contains the average experimentally obtained enhancement ratios for the tubes studied in this thesis which all had the same fin spacing of 1.5mm. Figure 5.18 shows a similar comparison under vacuum conditions. At atmospheric conditions, the predicted enhancement ratios from the Beatty and Katz model were closer to the experimentally obtained enhancement ratios than those predicted by the modified Rose model. But under vacuum conditions, the modified Rose model predictions were closer, and in several cases, the enhancement ratios were identical to the data. TABLES XI and XII tabulate predicted and experimental enhancement ratios of the rectangular shaped finned tubes, under atmospheric and vacuum conditions, respectively. In both TABLES, the enhancement ratio decreases as the thermal conductivity of the tube material decreases, as predicted by both models.

The Rose model [Ref. 8] was further modified to include a radiussed fin root, as given by equation (4.37). Using this

modified model, the predicted enhancement ratios were compared to the average experimental heat transfer enhancement ratios for deep radiussed root finned tubes in TABLES XIII and XIV. Clearly, the experimental heat transfer enhancement ratios are significantly lower than the enhancement ratios predicted by the active surface areas. TABLES XV and XVI contain a similar comparison for the shallow radiussed root finned tubes.

Figure 5.19 is a comparison of the Masuda and Rose model [Ref. 6] (equations 2.14, 2.15, 2.37, and 2.38) for the total surface area and active surface area enhancement ratios for rectangular shaped and radiussed root finned tubes. Using the Fortran Program HEATCOBB, the surface area ratios for the copper finned tube used by Briggs, Wen, and Rose [Ref. 28] were reproduced in Figure 5.19. Their finned tubes had a fin height of 1.59mm, a fin thickness of 0.5mm, and a fin spacing of 1.0mm and 1.5mm (although numerous theoretical spacings are included in Figure 5.19). Their tubes had as inside diameter of 9.53mm, and a root diameter of 12.7mm. In Figure 5.19, comparing the curves for the tube dimensions used in [Ref. 28] to the rectangular shaped finned tube dimensions in this thesis, the change in the total surface area from a rectangular shaped finned tube to a radiussed root finned (equation (2.14) minus equation (2.37)) decreased nearly twice the amount, 13.5% to 8.9% respectively. Also, the increase in the active surface area (equation (2.38) minus equation (2.15)) was less for the finned tube in this thesis compared

to the finned tube in [Ref. 28], 43% and 56%, respectively. TABLE XVII is a comparison of the experimentally obtained heat transfer enhancement ratios (where $\epsilon_{\Delta T}$ is the average enhancement ratio over the range of temperature differences based on a smooth tube of root diameter for the rectangular shaped finned tube and $\epsilon_{\Delta T,F}$ is for the deep radiussed root finned tube of the same root diameter) and the active surface area enhancement ratios (where ϵ_{AA} is the active area enhancement by dividing the unblanked finned tube surface area by the surface area of a smooth tube of root diameter and ϵ_{AR} is similar but for the deep radiussed root finned tube) for rectangular shaped and radiussed root finned tubes. The $\epsilon_{\Delta T}$ values were obtained from the ratio of the aplhas listed in TABLE III. Rose et al [Ref. 28] felt that the small experimental enhancement from radiussing the fin based root (1.09) seemed somewhat anomalous compared to the higher ratio of 1.53 obtained from the active surface area ratios, and the data needed to be repeated. In this thesis study, the ratio of the heat transfer enhancement ratios for the radiussed root finned tube divided by the rectangular shaped finned tube were less than one whereas the ratio of the active surface area enhancement ratios was 1.38. This can be attributed to many things, including less total surface area for the radiussed root compared to [Ref. 28], less of an increase in active surface area when compared to [Ref. 28], the actual amount of

condensate retained between fins of different geometries, and the actual flooding angle for the radiussed root finned tubes.

Various assumptions have been made in analyzing the data obtained in this thesis study, but it is evident that more data is required before all the mysteries associated with this complex condensation process can be unravelled.

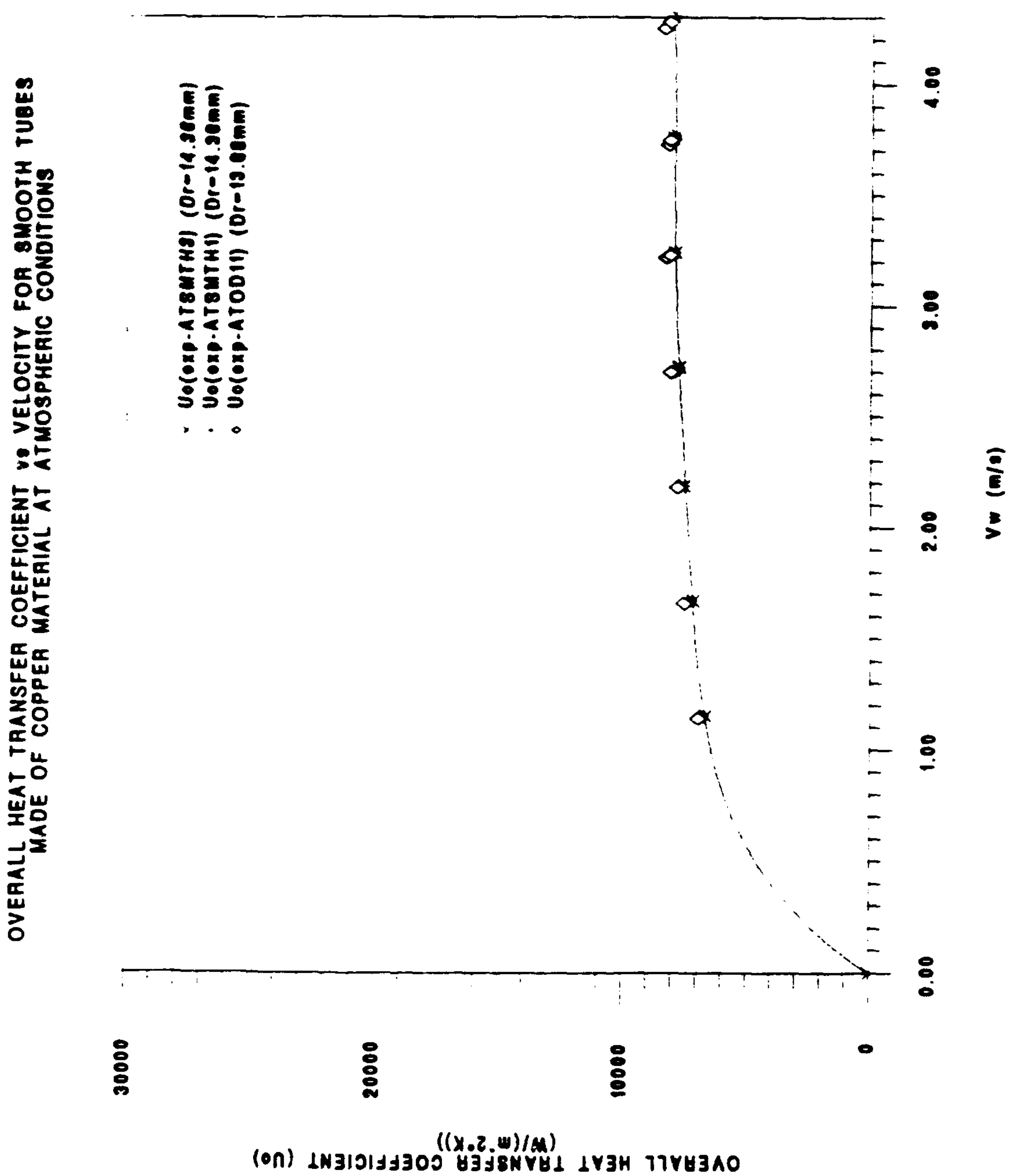

Figure 5.1 Overall Heat Transfer Coefficient vs Velocity for Smooth Tubes made of Copper Material at Atmospheric Conditions

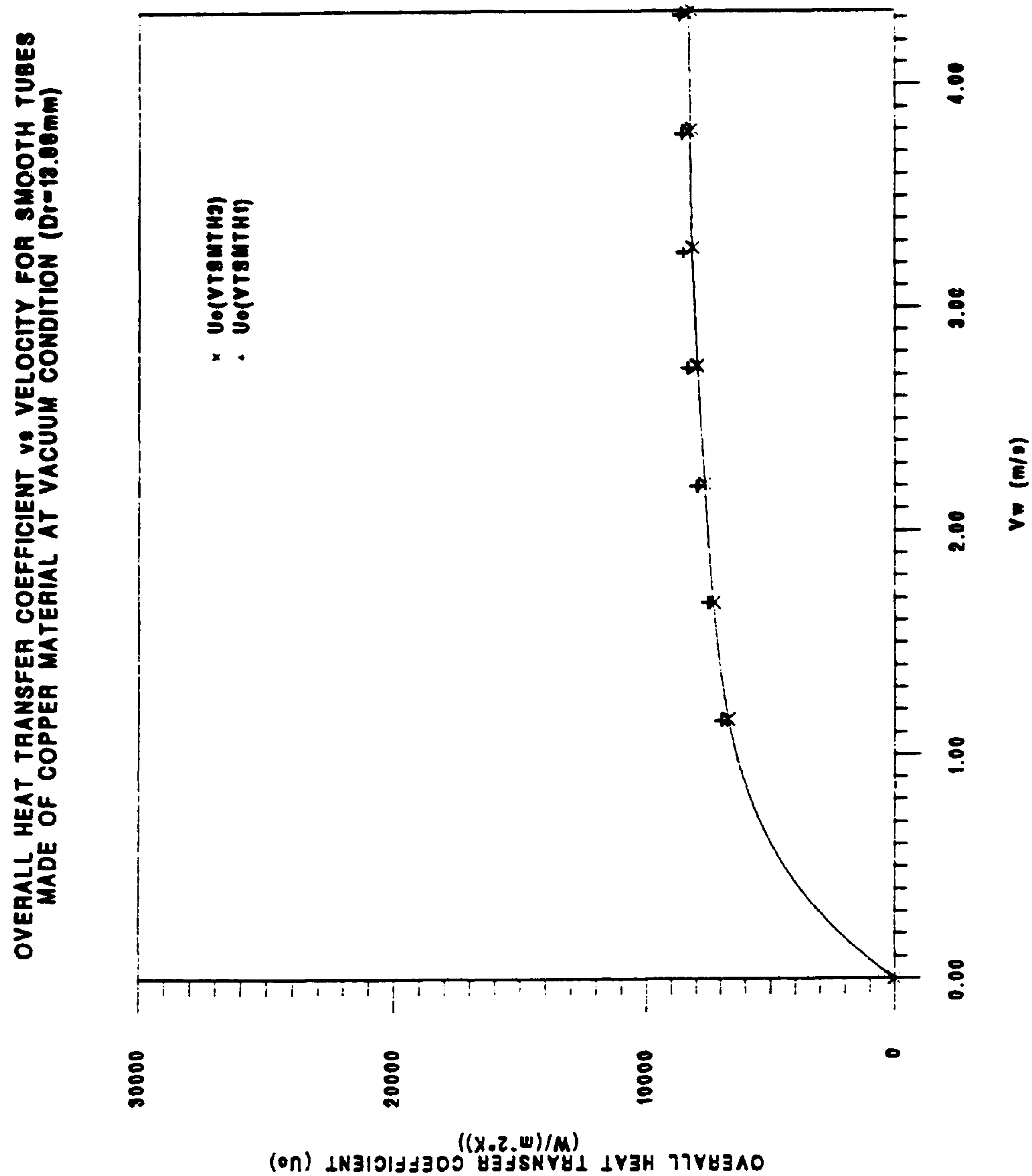

Figure 5.2 Overall Heat Transfer Coefficient vs Velocity for Smooth Tubes made of Copper Material at Vacuum Conditions (D_r= 13.88mm)

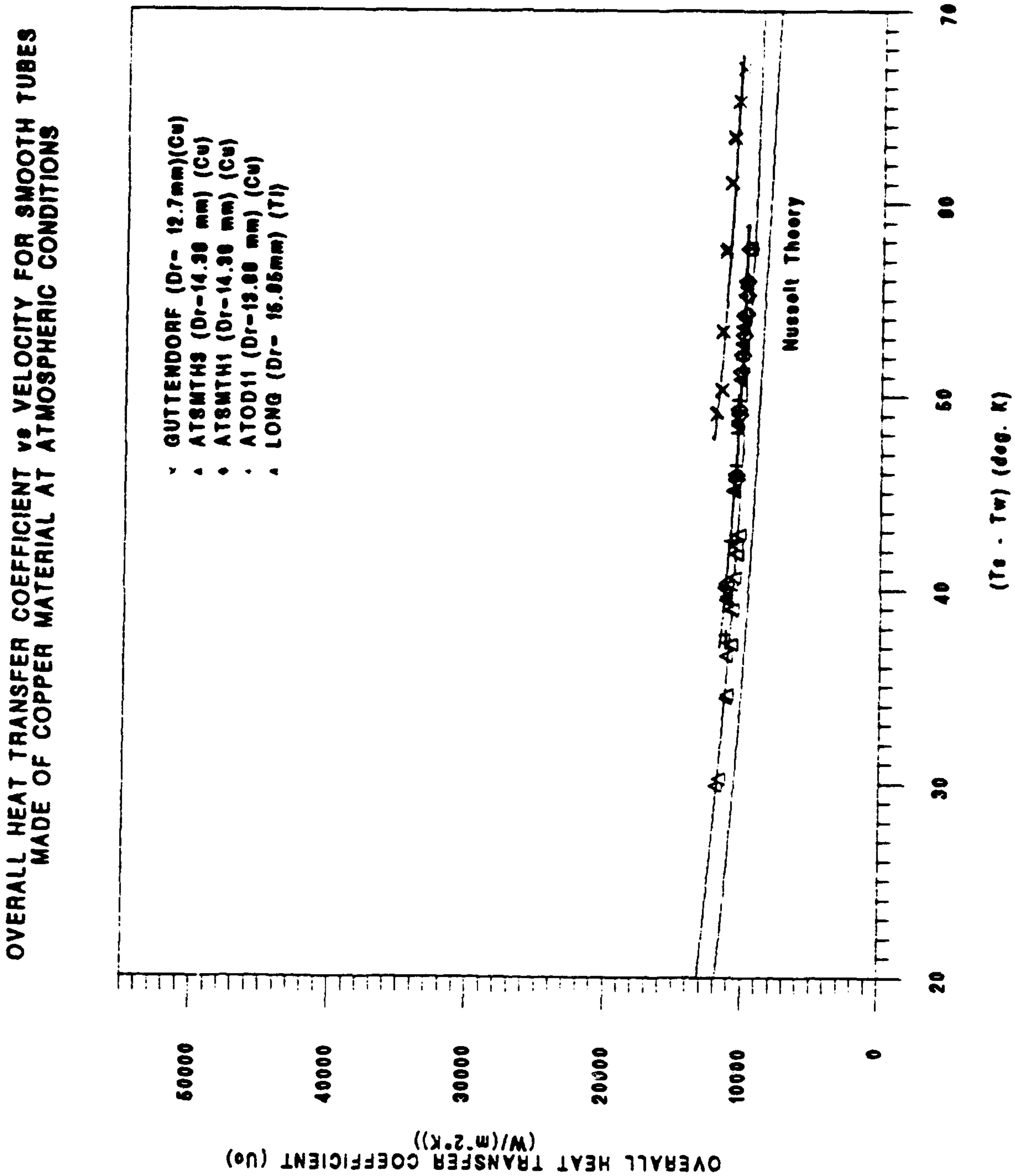

Figure 5.3 Comparison of Smooth Tubes at Atmospheric Conditions with Different Diameters and Materials

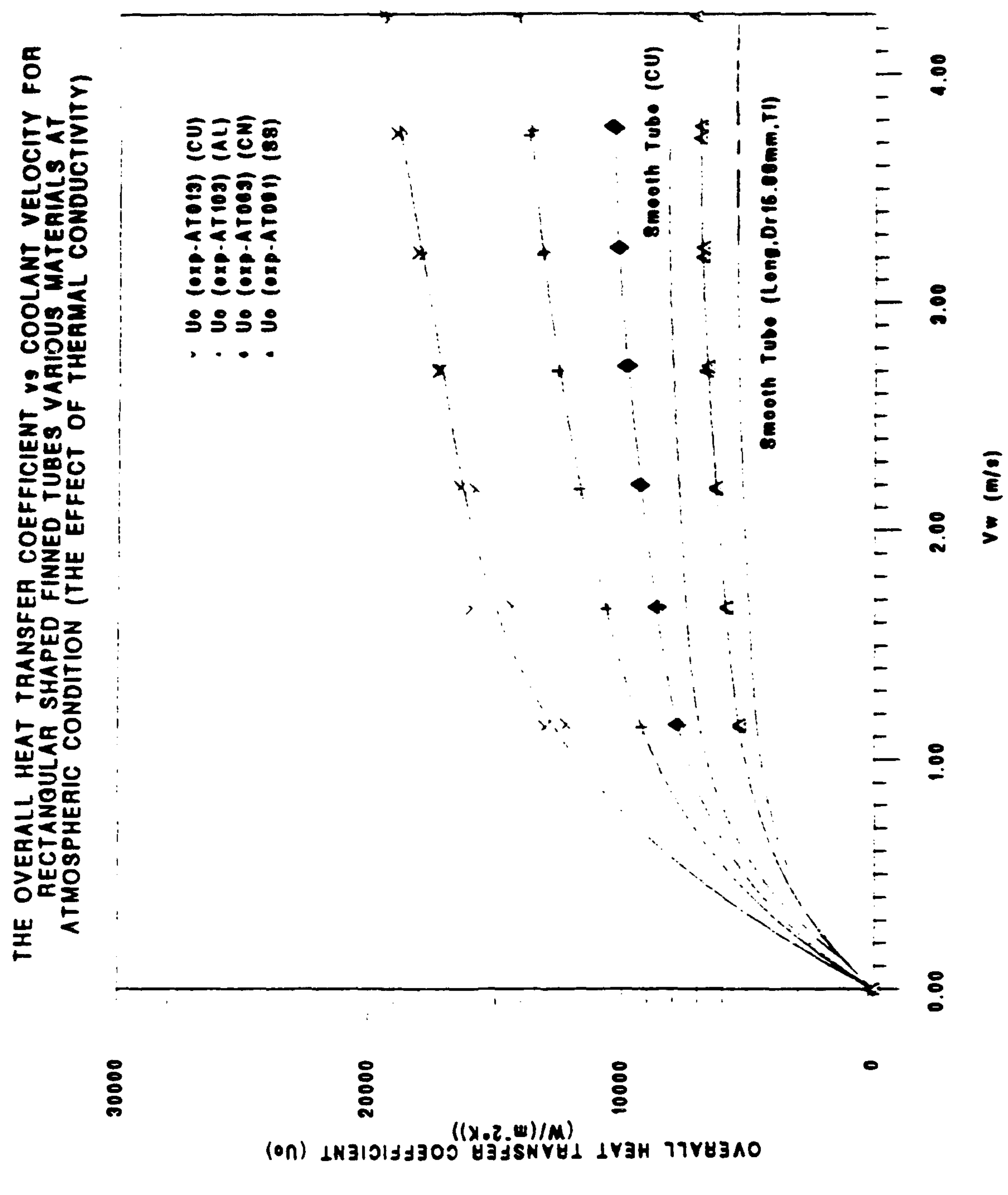

Figure 5.4 The Overall Heat Transfer Coefficient vs Coolant Velocity for Rectangular Shaped Finned Tubes for Various Materials at Atmospheric Conditions (the effect of thermal conductivity)

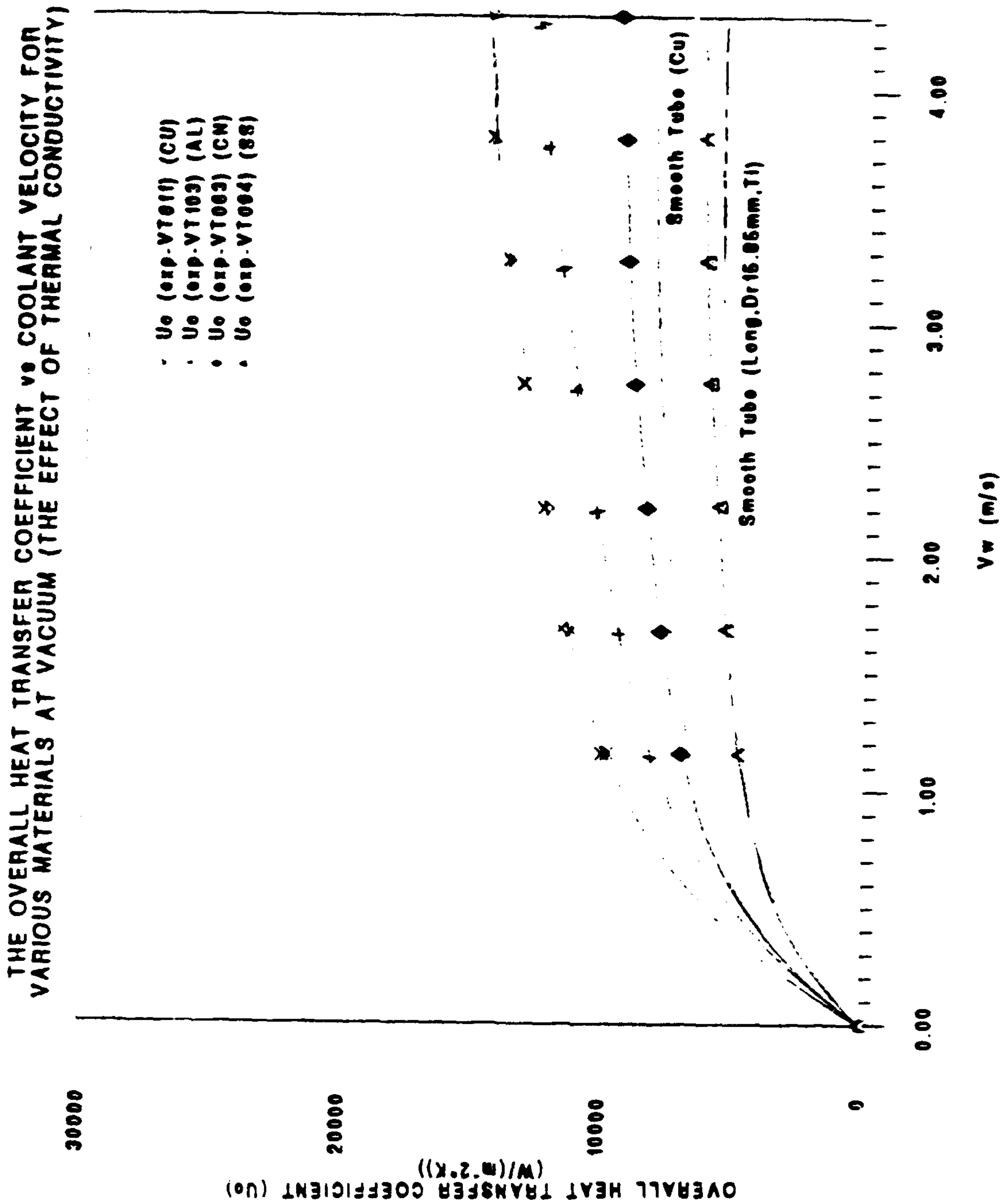

Figure 5.5 The Overall Heat Transfer Coefficient vs Coolant Velocity for Rectangular Shaped Finned tubes Various for Materials at Vacuum Conditions (the effect of thermal conductivity)

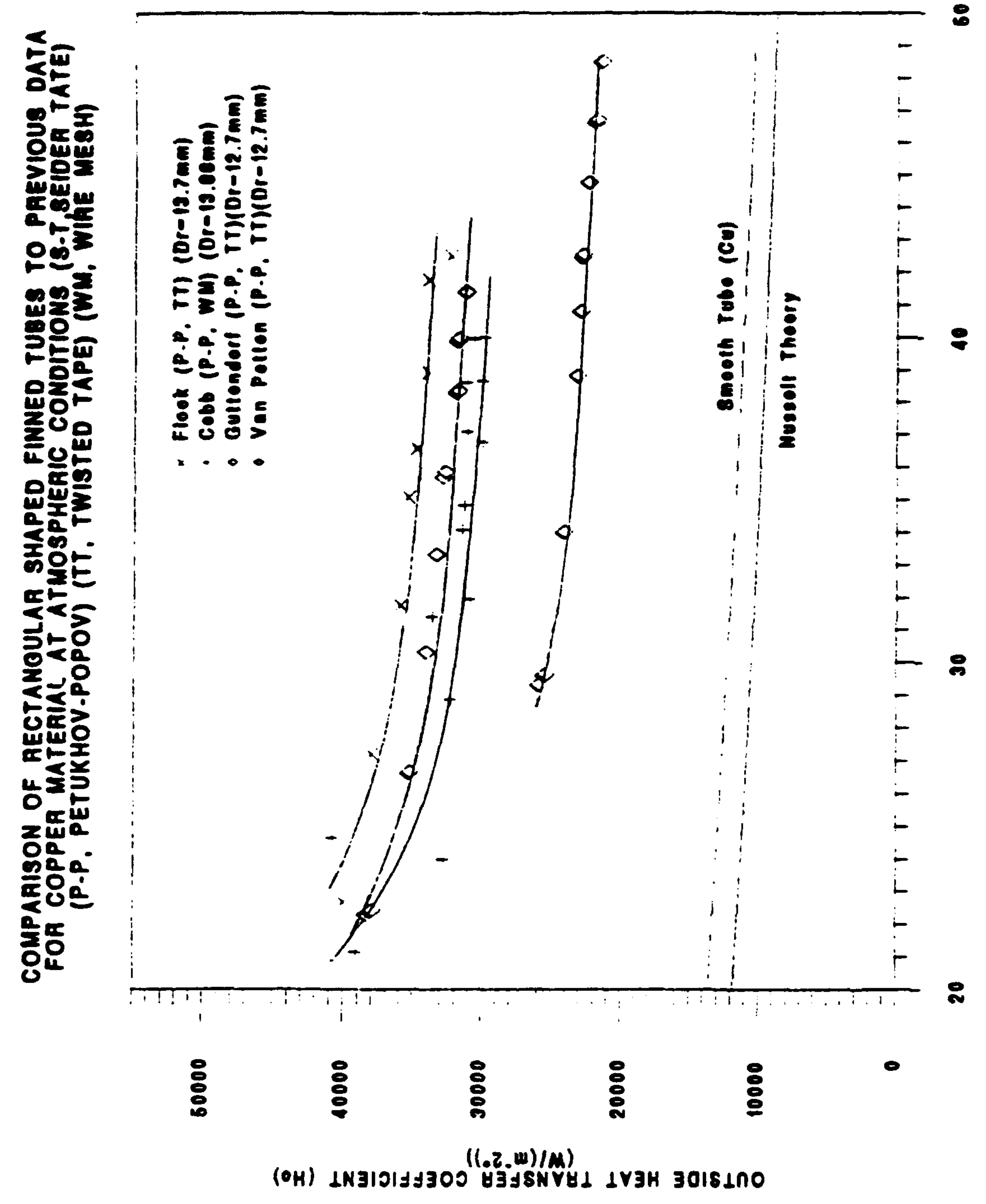

Figure 5.6 Comparison of Rectangular Shaped Finned Tubes to Previous Data for Copper Material at Atmospheric Conditions (S-T (Seider Tate) and P-P (Petukhov Popov) inside correlations, TT (Twisted Tape) and WM are type of Inserts)

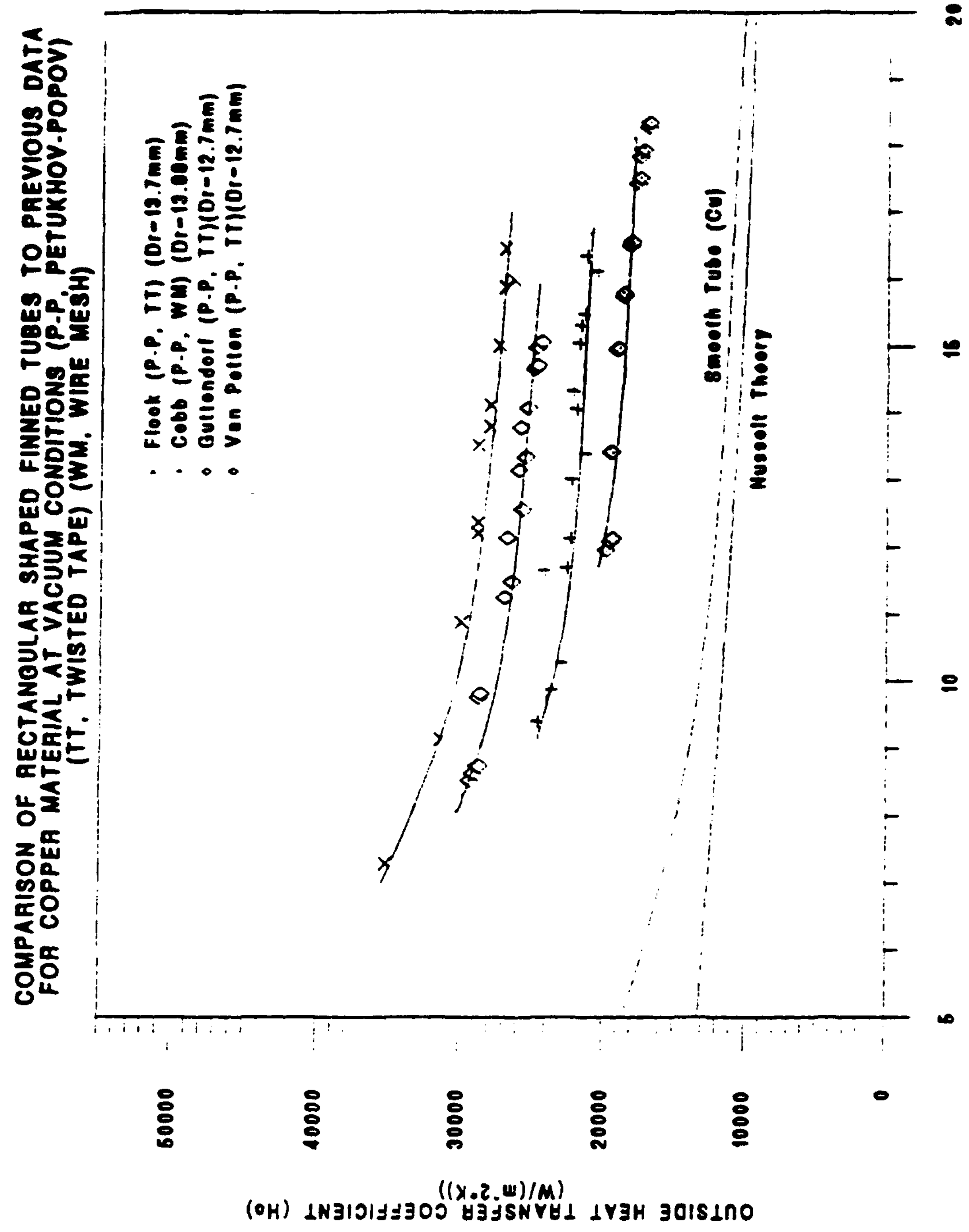

Figure 5.7 Comparison of Rectangular Shaped Finned Tubes to Previous Data for Copper Material at Vacuum Conditions (S-T (Seider Tate) and P-P (Petukhov Popov) inside correlations and TT (Twisted Tape) and WM (Wire Mesh) are type of Inserts)

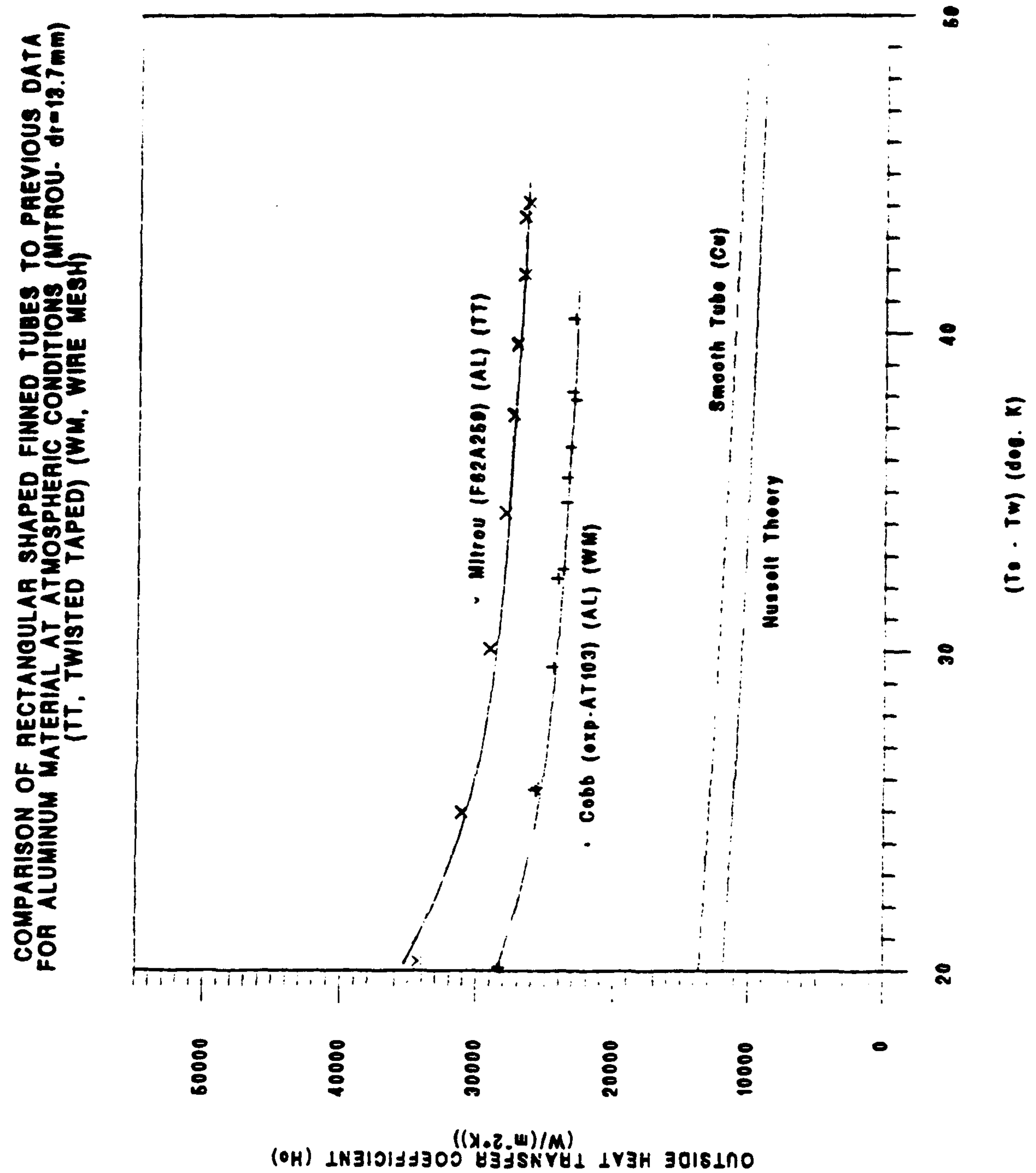

Figure 5.8 Comparison of Rectangular Shaped Finned Tubes to Previous Data for Aluminum Material at Atmospheric Conditions (Mitrou D_r= 13.7mm) (TT (Twisted Tape) and WM (Wire Mesh) are type of Inserts)

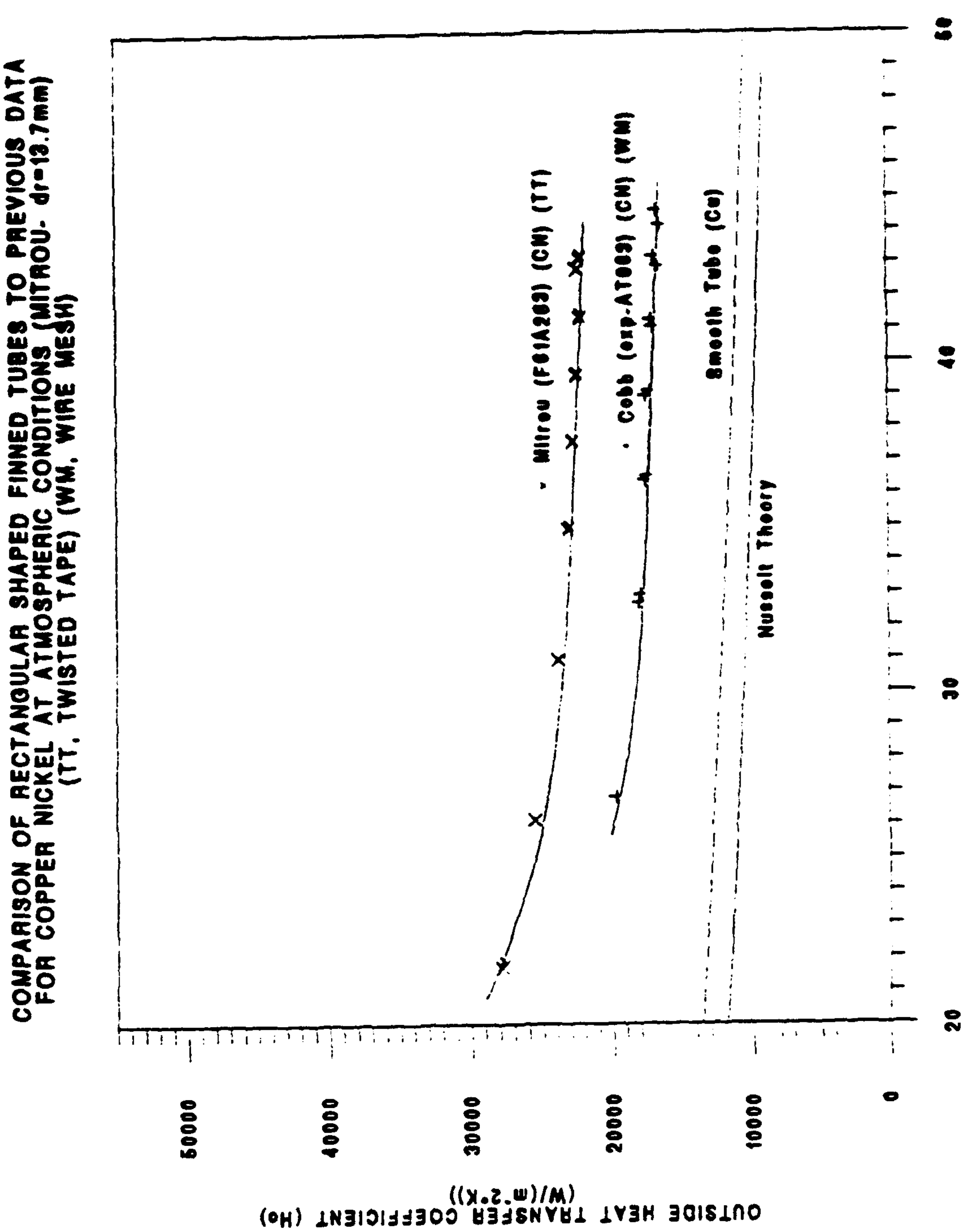

Figure 5.9 Comparison of Rectangular Shaped Finned Tubes to Previous Data for Copper Nickel Material at Atmospheric Conditions (Mitrou D_r= 13.7mm) (TT (Twisted Tape) and WM (Wire Mesh) are type of Inserts)

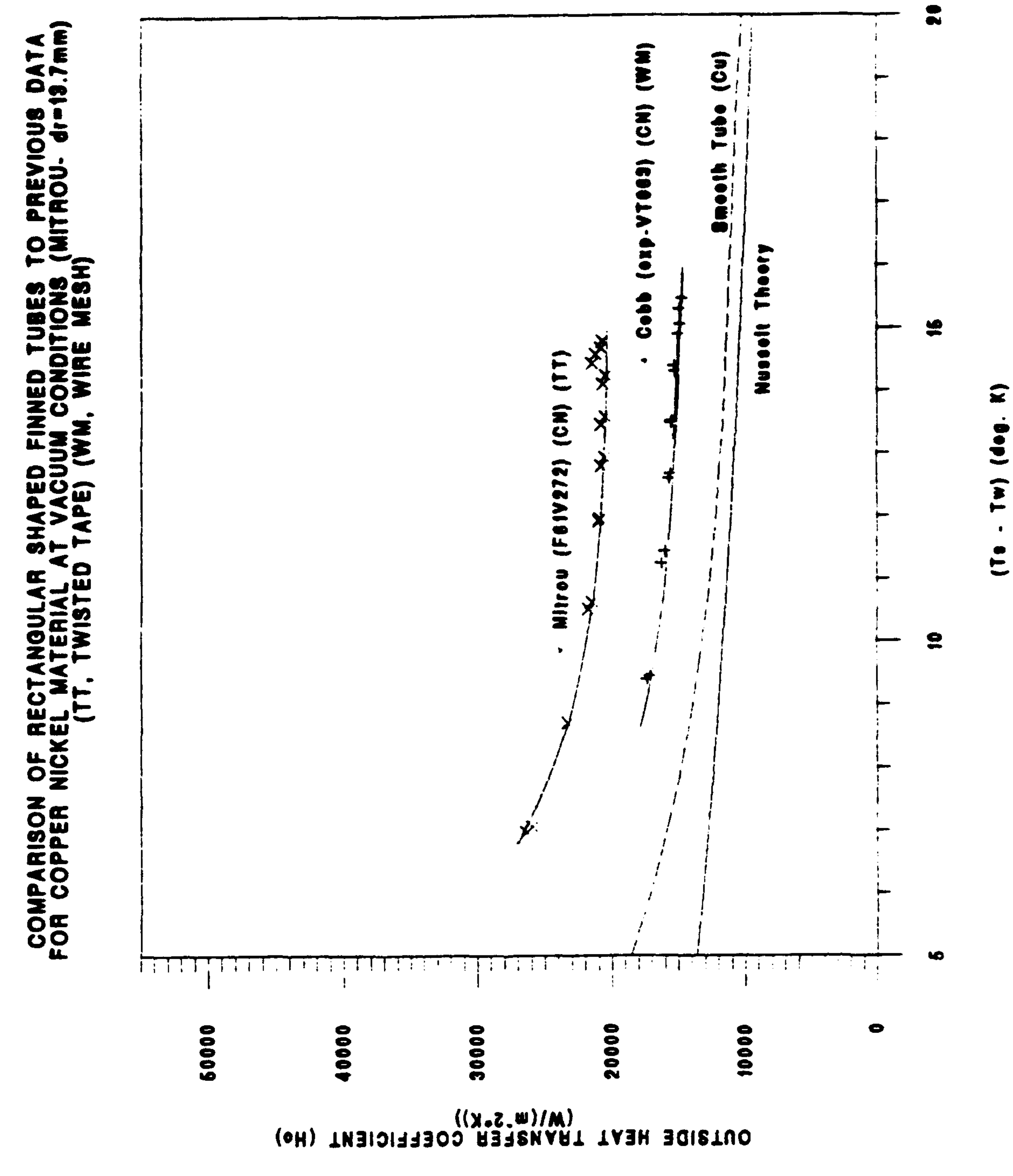

Figure 5.10 Comparison of Rectangular Shaped Finned Tubes to Previous Data for Copper Nickel at Vacuum Conditions (Mitrou D_r= 13.7mm) (TT (Twisted Tape) and WM (Wire Mesh) are type of Inserts)

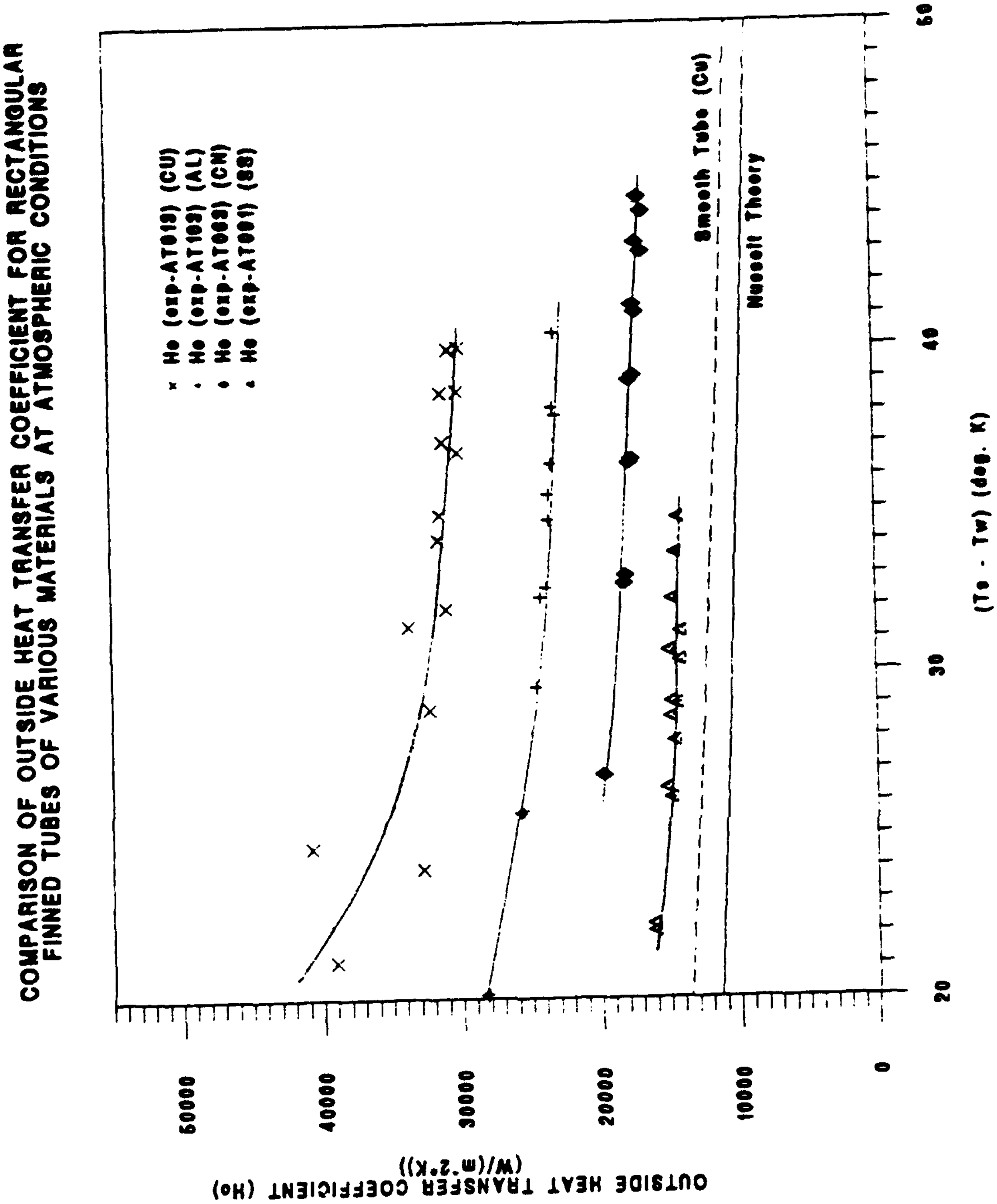

Figure 5.11 Comparison of Outside Heat Transfer Coefficient for Rectangular Shaped Finned Tubes for Various Materials at Atmospheric Conditions

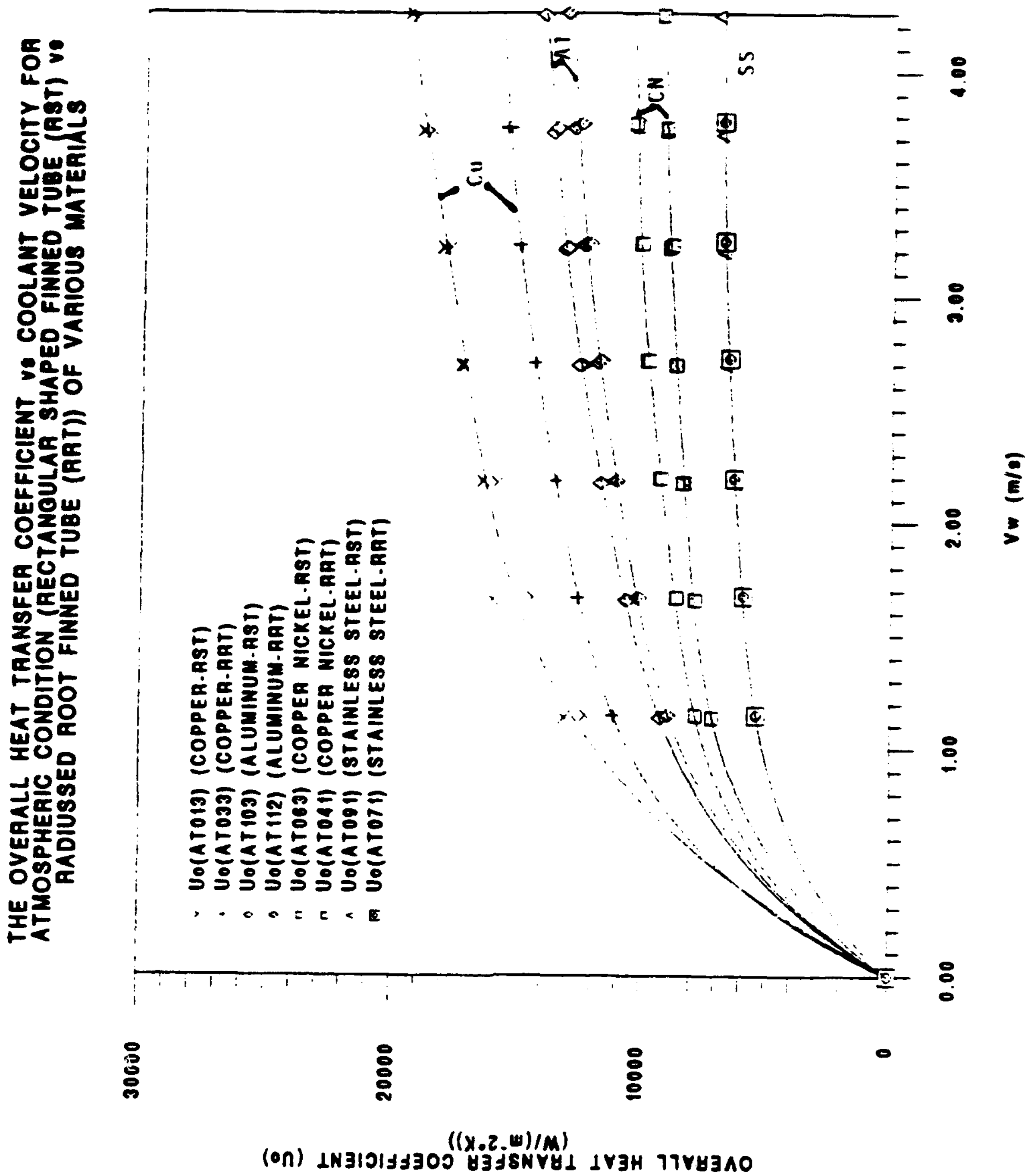

Figure 5.12 The Overall Heat Transfer Coefficient vs Coolant Velocity for Atmospheric Conditions (Rectangular Shaped Finned Tube (RST) vs Radiussed Root Finned Tubes (RRT)) for Various Materials

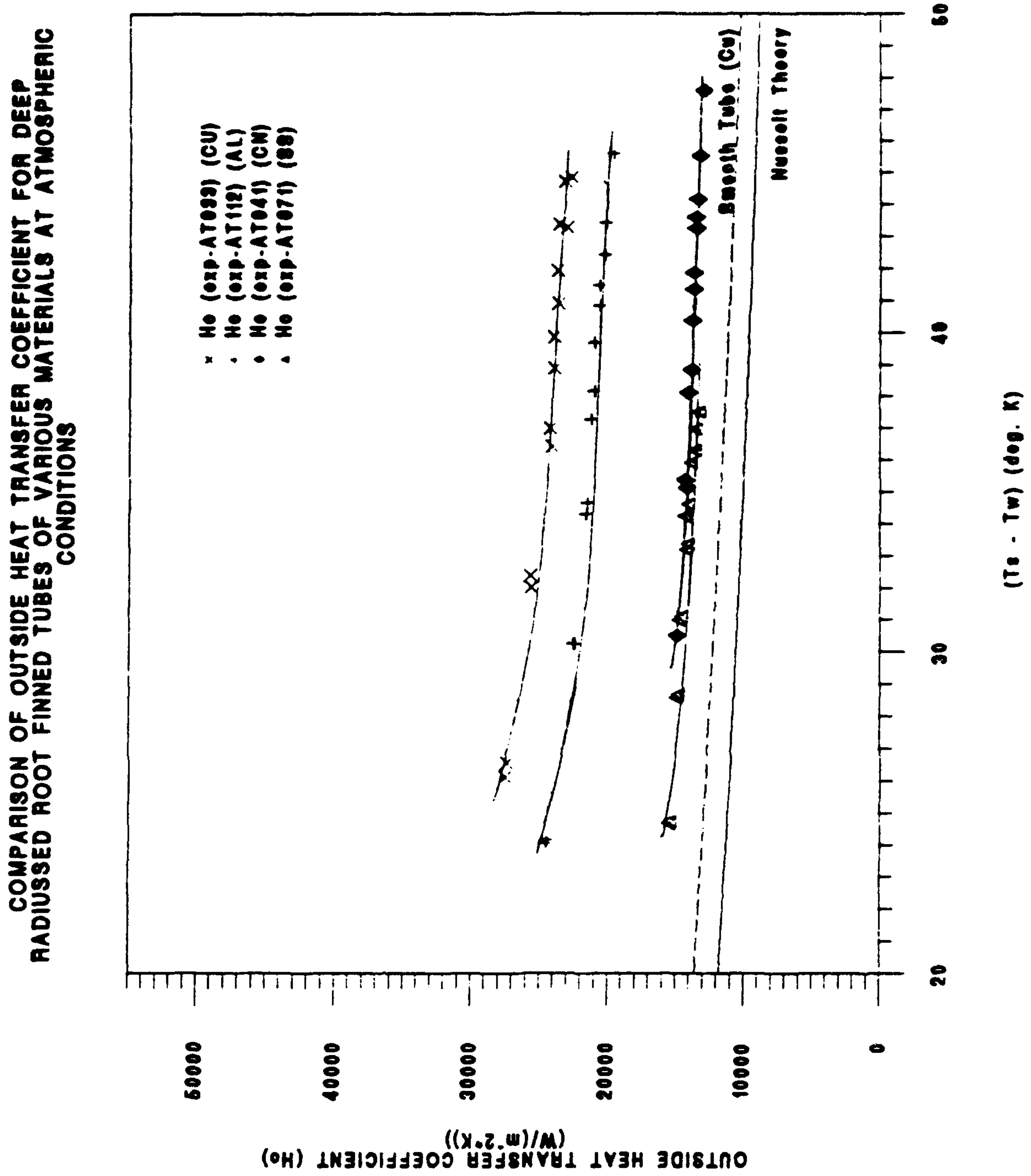

Figure 5.13 Comparison of Outside Heat Transfer Coefficient for Deep Radiussed Root Finned Tubes of Various Materials at Atmospheric Conditions

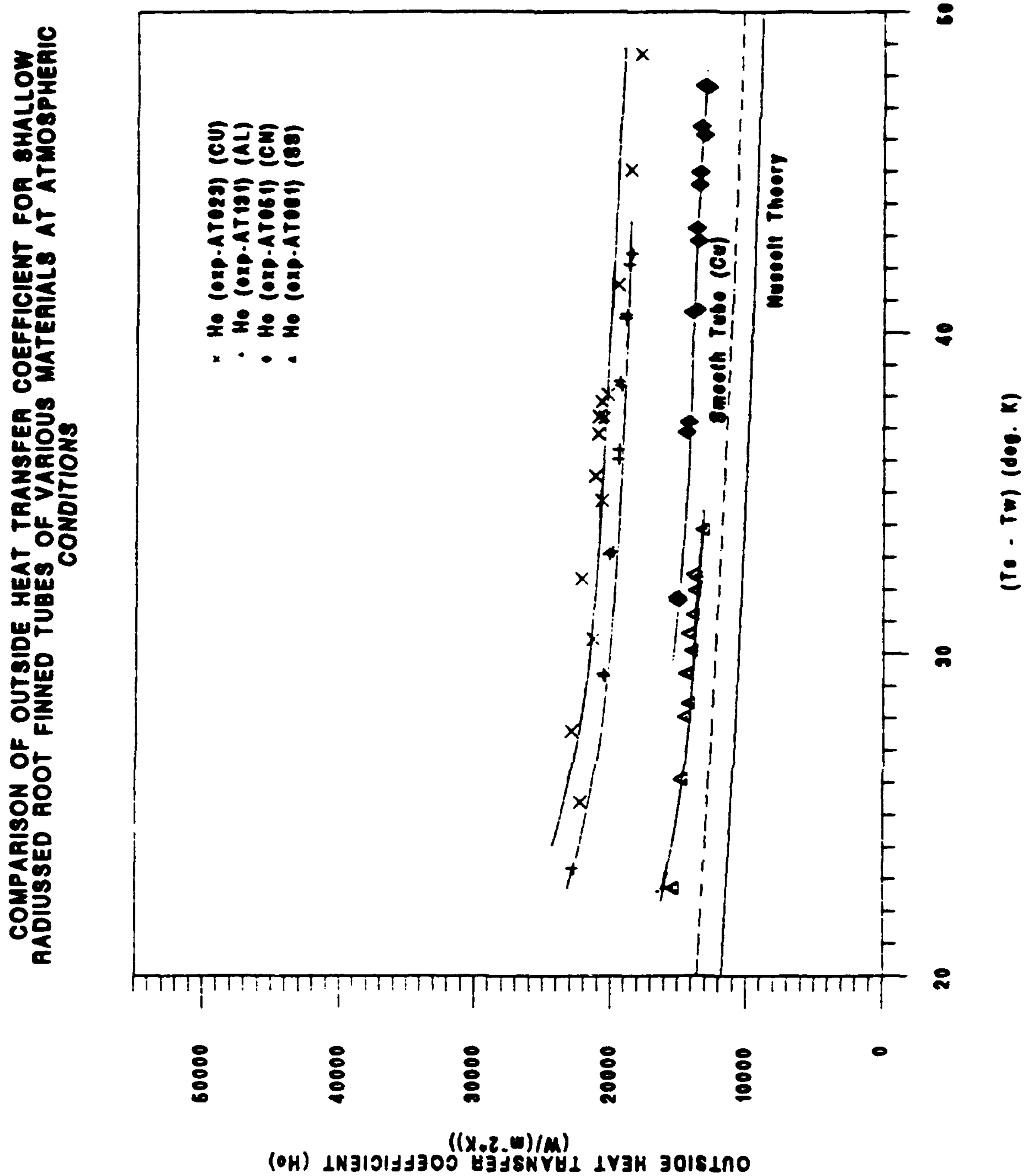

Figure 5.14 Comparison of Outside Heat Transfer Coefficient of Shallow Radiussed Root Finned Tubes of Various Materials at Atmospheric Conditions

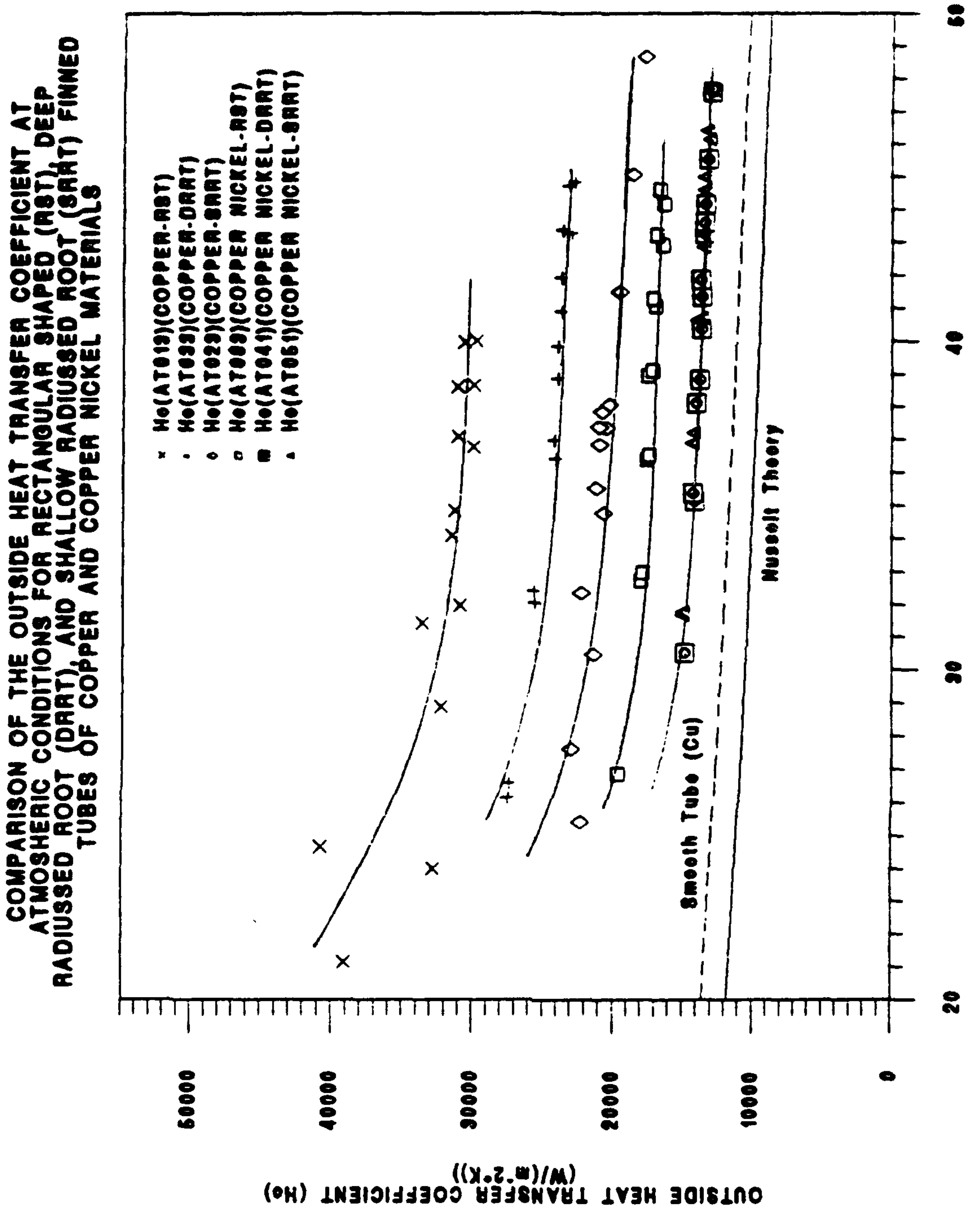

Figure 5.15 Comparison of the Outside Heat Transfer Coefficient at Atmospheric Conditions for Rectangular Shaped (RST), Deep Radiussed Root (DRRT), and Shallow Radiussed Root (SRRT) Finned Tubes of Copper and Copper Nickel Materials

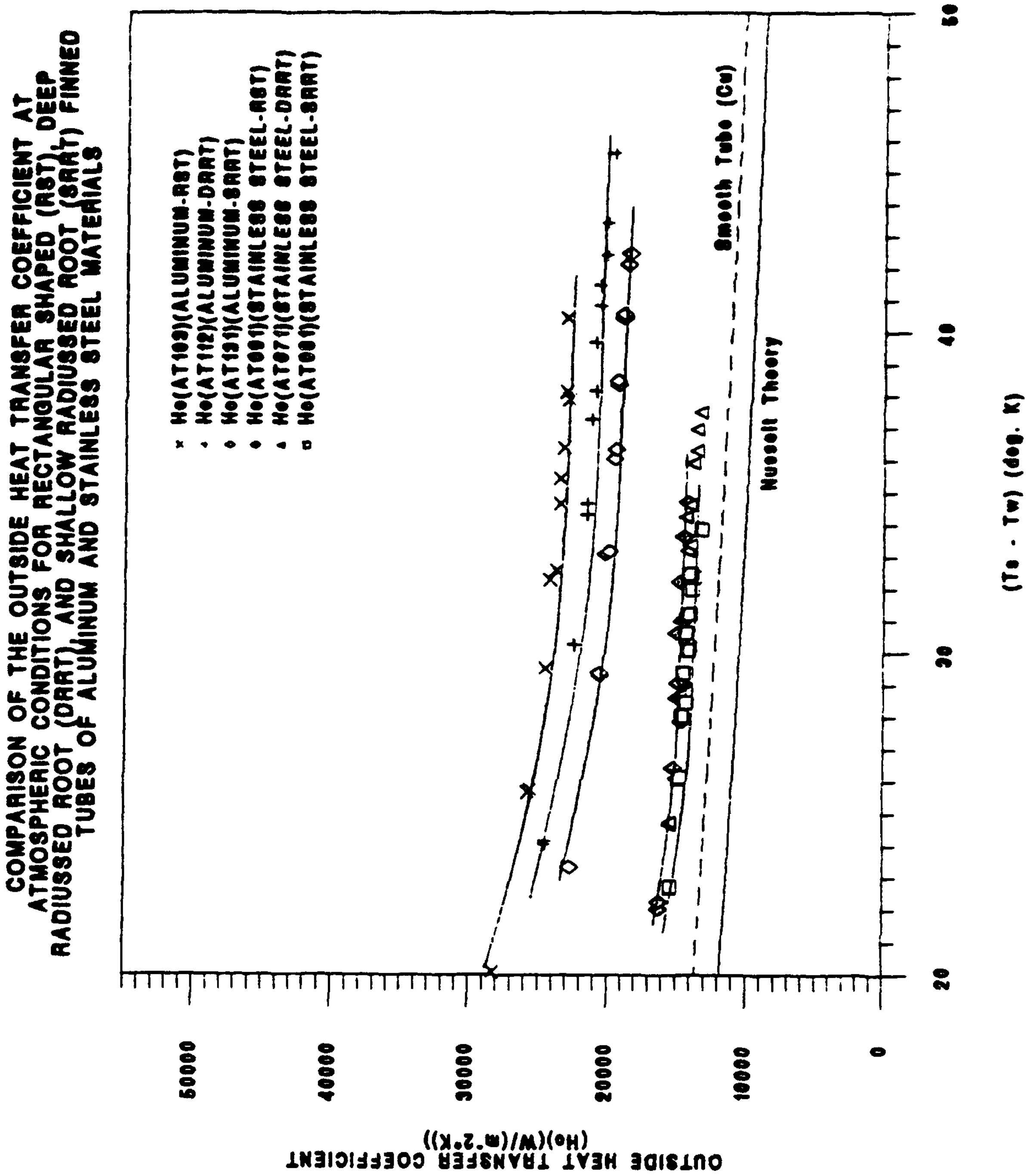

Figure 5.16 Comparison of the Outside Heat Transfer Coefficient at Atmospheric Conditions for Rectangular Shaped (RST), Deep Radiussed Root (DRRT), and Shallow Radiussed Root (SRRT) Finned Tubes of Aluminum and Stainless Steel Materials

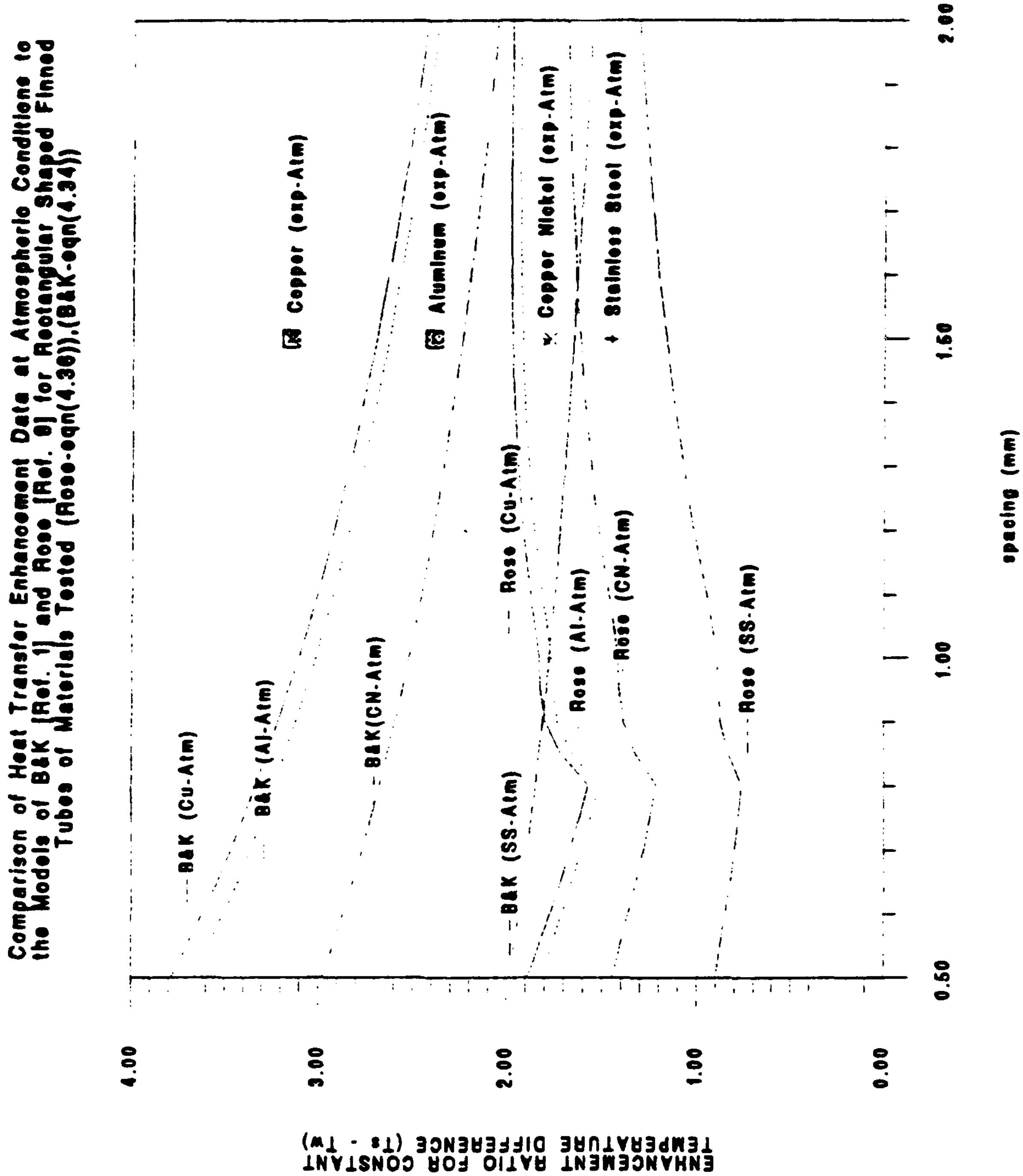

Figure 5.17 Comparison of Heat Transfer Enhancement Data at Atmospheric Conditions to the models of Beatty and Katz [Ref. 1] and Rose [Ref. 8] for Rectangular Shaped Finned Tubes of Materials Tested

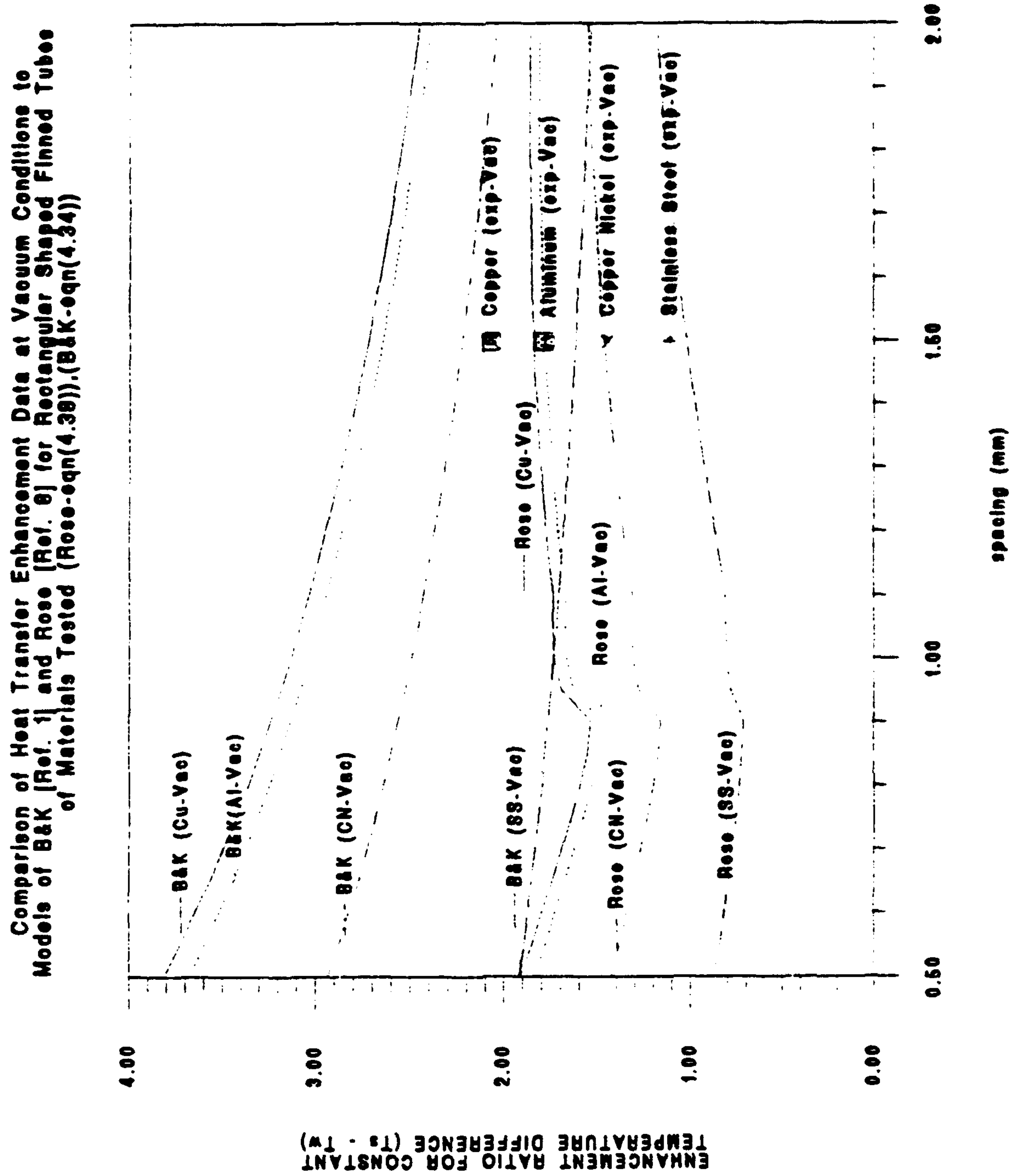

Figure 5.18 Comparison of Heat Transfer Enhancement Data at Vacuum conditions to the models of Beatty and Katz [Ref. 1] and Rose [Ref. 8] for Rectangular Shaped Finned Tubes of materials tested (B&K-eqn(4.34) and Rose-eqn(4.36))

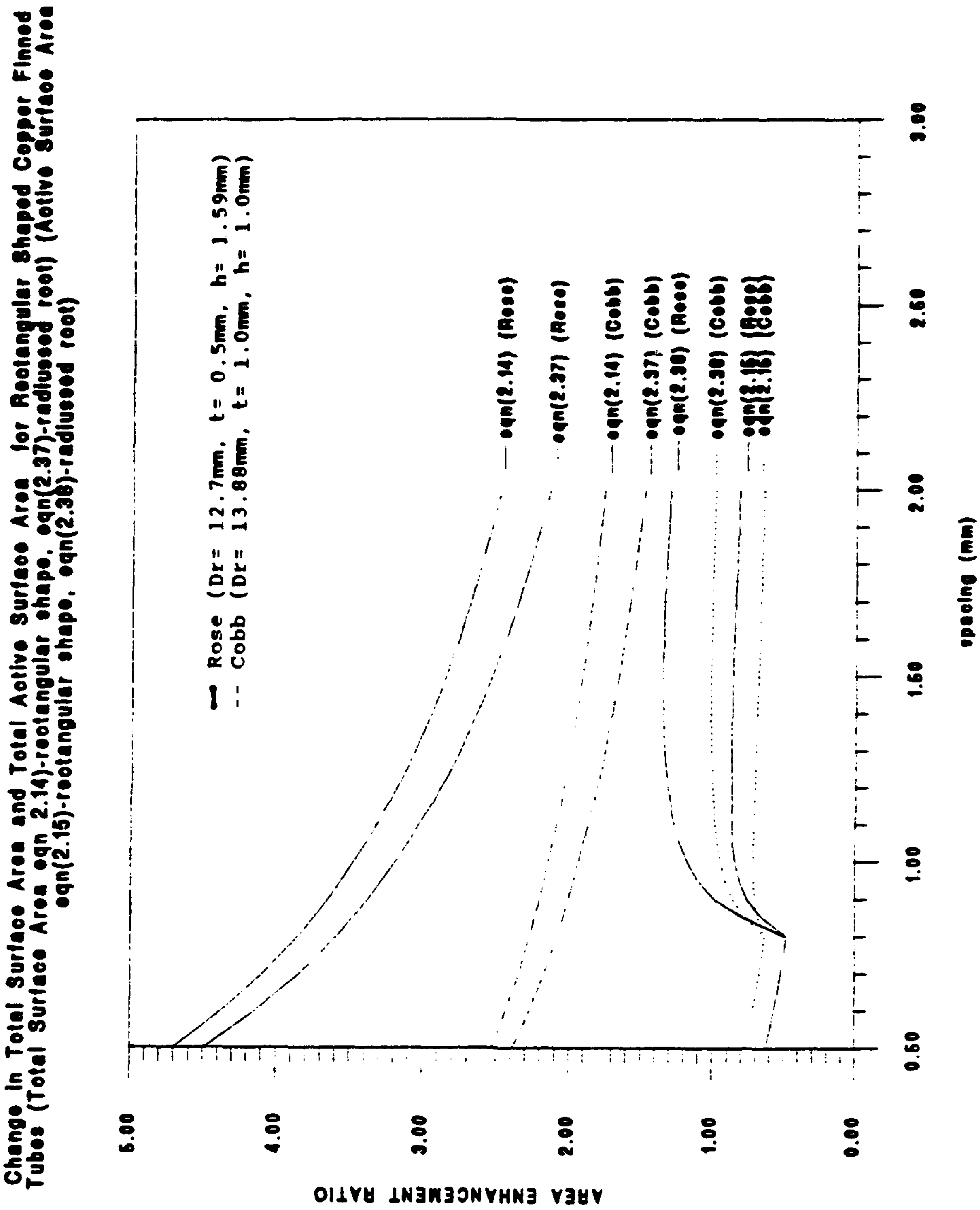

Figure 5.19 Change in Total and Active Surface Area for Rectangular Shaped Copper Finned Tubes (Total Surface Area eqn(2.14) rectangular shaped, eqn(2.37) radiussed root) (Active Surface Area eqn(2.15) rectangular shaped, eqn(2.38) radiussed root)

TABLE III. INSIDE LEADING COEFFICIENTS AND OUTSIDE ALPHA VALUES FOR ATMOSPHERIC CONDITIONS.

Tube No.	Tube Type	Tube Material	Ci (Atm)	Alpha (Atm)
1	Rectangular Fin	Copper (Pure)	3.11	2.19
2	Shallow Fillet	Copper (Pure)	3.08	1.50
3	Deep Fillet	Copper (Pure)	3.02	1.85
4	Deep Fillet	Copper Nickel (90/10)	2.65	1.05
5	Shallow Fillet	Copper Nickel (90/10)	2.67	1.06
6	Rectangular Fin	Copper Nickel (90/10)	2.67	1.30
7	Deep Fillet	Stainless Steel (316)	2.26	1.01
8	Shallow Fillet	Stainless Steel (316)	2.35	0.98
9	Rectangular Fin	Stainless Steel (316)	2.10	1.07
10	Rectangular Fin	Aluminum (Pure)	2.29	1.74
11	Deep Fillet	Aluminum (Pure)	2.33	1.56
13	Shallow Fillet	Aluminum (Pure)	2.25	1.44
OD1	Smooth	Copper (Pure)	2.82	0.85
SMTH	Smooth	Copper (Pure)	2.80	0.85

TABLE IV. INSIDE LEADING COEFFICIENTS AND OUTSIDE ALPHA VALUES FOR VACUUM CONDITIONS.

Tube No.	Tube Type	Tube Material	Ci (Vac)	Alpha (Vac)
1	Rectangular Fin	Copper (Pure)	2.99	1.50
2	Shallow Fillet	Copper (Pure)	2.91	1.14
3	Deep Fillet	Copper (Pure)	3.03	1.30
4	Deep Fillet	Copper Nickel (90/10)	2.48	0.86
5	Shallow Fillet	Copper Nickel (90/10)	2.37	0.83
6	Rectangular Fin	Copper Nickel (90/10)	2.42	1.06
7	Deep Fillet	Stainless Steel (316)	2.11	0.78
8	Shallow Fillet	Stainless Steel (316)	2.15	0.80
9	Rectangular Fin	Stainless Steel (316)	1.93	0.77
10	Rectangular Fin	Aluminum (Pure)	2.00	1.30
11	Deep Fillet	Aluminum (Pure)	2.30	1.18
13	Shallow Fillet	Aluminum (Pure)	2.24	1.05
SMTH	Smooth	Copper (Pure)	2.78	0.81

TABLE V. OUTSIDE HEAT TRANSFER COEFFICIENT, h_o (W/(m^2*K)), FOR ATMOSPHERIC CONDITIONS FOR ΔT= 30°K.

TUBE TYPE	Copper	Aluminum	Copper Nickel	Stainless Steel
Rectangular	33100	24500	18950	14400
Deep Radiussed	26600	22750	15500	14450
Shallow Radiussed	22250	20500	15800	13800
Smooth Tube	12500	NA	NA	NA
Nusselt Theory	11000	NA	NA	NA

TABLE VI. OUTSIDE HEAT TRANSFER COEFFICIENT, h_o (W/(m^2*K)), FOR VACUUM CONDITIONS FOR ΔT= 12°K.

Tube Type	Copper	Aluminum	Copper Nickel	Stainless Steel
Rectangular	22900	20950	16400	13000
Deep Radiussed	20100	18000	13700	11900
Shallow Radiussed	17000	15800	13300	12000
Smooth Tube	12800	NA	NA	NA
Nusselt Theory	11700	NA	NA	NA

TABLE VII. **ENHANCEMENT RATIO BASED ON SMOOTH TUBE, $\epsilon_{\Delta T} = (h_f/h_{smth})_{\Delta T}$, FOR ATMOSPHERIC CONDITIONS FOR $\Delta T = 30^{\circ}K$.**

Tube Type	Copper	Aluminum	Copper Nickel	Stainless Steel
Rectangular	2.65	1.96	1.52	1.15
Deep Radiussed	2.13	1.82	1.24	1.16
Shallow Radiussed	1.78	1.64	1.26	1.10

TABLE VIII. **ENHANCEMENT RATIO BASED ON NUSSELT THEORY, $\acute{\epsilon}_{\Delta T} = (h_f/h_{nuss})_{\Delta T}$, FOR ATMOSPHERIC CONDITIONS FOR $\Delta T = 30^{\circ}K$.**

Tube Type	Copper	Aluminum	Copper Nickel	Stainless Steel
Rectangular	3.01	2.23	1.72	1.31
Deep Radiussed	2.42	2.07	1.41	1.31
Shallow Radiussed	2.02	1.86	1.44	1.26

TABLE IX. ENHANCEMENT RATIO BASED ON SMOOTH TUBE, $\epsilon_{\Delta T} = (h_f/h_{smth})_{\Delta T}$, FOR VACUUM CONDITIONS FOR $\Delta T = 12^{\circ}K$.

Tube Type	Copper	Aluminum	Copper Nickel	Stainless Steel
Rectangular	1.79	1.64	1.28	1.02
Deep Radiussed	1.57	1.41	1.07	0.93
Shallow Radiussed	1.33	1.23	1.04	0.94

TABLE X. ENHANCEMENT RATIO BASED ON NUSSELT THEORY, $\acute{\epsilon}_{\Delta T} = (h_f/h_{NUSS})_{\Delta T}$, FOR VACUUM CONDITIONS FOR $\Delta T = 12^{\circ}K$.

Tube Type	Copper	Aluminum	Copper Nickel	Stainless Steel
Rectangular	1.96	1.79	1.40	1.11
Deep Radiussed	1.72	1.54	1.17	1.02
Shallow Radiussed	1.45	1.35	1.14	1.03

TABLE XI. ENHANCEMENT RATIO AVERAGED OVER THE RANGE OF ΔT FOR RECTANGULAR SHAPED FINNED TUBES FOR ATMOSPHERIC CONDITIONS BASED ON NUSSELT THEORY, $\epsilon_{\Delta T} = (h_f/h_{NUSS})_{\Delta T}$.

Tube Material	Tube No.	ϵ_{BK} eqn (4.34)	ϵ_{Rose} eqn (4.36)	ϵ_{exp} (h_{exp}/h_{NUSS})
Copper	1	2.71	1.97	3.05
Aluminum	10	2.62	1.91	2.40
Copper Nickel	6	2.25	1.61	1.79
Stainless Steel	9	1.61	1.14	1.47

TABLE XII. ENHANCEMENT RATIO AVERAGED OVER THE RANGE OF ΔT FOR RECTANGULAR SHAPED FINNED TUBES FOR VACUUM CONDITIONS BASED ON NUSSELT THEORY, $\epsilon_{\Delta T} = (h_f/h_{NUSS})_{\Delta T}$.

Tube Material	Tube No.	ϵ_{BK} eqn(4.34)	ϵ_{Rose} eqn (4.36)	ϵ_{exp} (h_{exp}/h_{NUSS})
Copper	1	2.73	1.85	2.07
Aluminum	10	2.62	1.78	1.79
Copper Nickel	6	2.23	1.47	1.45
Stainless Steel	9	1.59	1.00	1.06

TABLE XIII. **ENHANCEMENT RATIO AVERAGED OVER THE RANGE OF ΔT FOR DEEP RADIUSSED ROOT FINNED TUBES FOR ATMOSPHERIC CONDITIONS BASED ON NUSSELT THEORY, $\epsilon_{\Delta T} = (h_f/h_{NUSS})_{\Delta T}$.**

Tube Material	Tube No.	ϵ_{Rose} Modified Rose eqn (4.40)	ϵ_{exp} (h_{exp}/h_{NUSS})
Copper	3	4.45	2.53
Aluminum	11	4.33	2.14
Copper Nickel	4	3.56	1.42
Stainless Steel	7	2.31	1.38

TABLE XIV. **ENHANCEMENT RATIO AVERAGED OVER THE RANGE OF ΔT FOR DEEP RADIUSSED ROOT FINNED TUBES FOR VACUUM CONDITIONS BASED ON NUSSELT THEORY, $\epsilon_{\Delta T} = (h_f/h_{NUSS})_{\Delta T}$.**

Tube Material	Tube No.	ϵ_{Rose} Modified Rose eqn (4.40)	ϵ_{exp} (h_{exp}/h_{NUSS})
Copper	3	4.31	1.79
Aluminum	11	4.17	1.62
Copper Nickel	4	3.35	1.18
Stainless Steel	7	2.11	1.07

TABLE XV. ENHANCEMENT RATIO AVERAGED OVER THE RANGE OF ΔT FOR SHALLOW RADIUSSED ROOT FINNED TUBES FOR ATMOSPHERIC CONDITIONS BASED ON NUSSELT THEORY, $\acute{\epsilon}_{\Delta T} = (h_f/h_{NUSS})_{\Delta T}$.

Tube Material	Tube No.	$\acute{\epsilon}_{Rose}$ Modified Rose eqn (4.40)	$\acute{\epsilon}_{exp}$ (h_{exp}/h_{NUSS})
Copper	2	3.75	2.06
Aluminum	13	3.68	1.98
Copper Nickel	5	3.20	1.45
Stainless Steel	8	2.20	1.36

TABLE XVI. ENHANCEMENT RATIO AVERAGED OVER THE RANGE OF ΔT FOR SHALLOW RADIUSSED ROOT FINNED TUBES FOR VACUUM CONDITIONS BASED ON NUSSELT THEORY, $\acute{\epsilon}_{\Delta T} = (h_f/h_{NUSS})_{\Delta T}$.

Tube Material	Tube No.	$\acute{\epsilon}_{Rose}$ Modified Rose eqn (4.40)	$\acute{\epsilon}_{exp}$ (h_{exp}/h_{NUSS})
Copper	2	3.64	1.57
Aluminum	13	3.57	1.45
Copper Nickel	5	3.07	1.16
Stainless Steel	8	2.10	1.09

TABLE XVII. COMPARSION OF ACTIVE SURFACE AREA ENHANCEMENT RATIOS TO EXPERIMENTALLY OBTAINED HEAT TRANSFER ENHANCEMENT RATIOS.

Tube Material	ϵ_{AA} eqn (2.15)	ϵ_{AT} exp-RST	ϵ_{AR} eqn (2.38)	$\epsilon_{AT,F}$ exp-RRT	$\epsilon_{AR}/\epsilon_{AA}$	$\epsilon_{AT,F}/\epsilon_{AT}$
Cu Rose [Ref.28][1]	0.92	2.77	1.41	3.03	1.53	1.09
Cu	0.74	2.57	1.02	2.17	1.38	0.84
Al	0.74	2.05	1.02	1.84	1.38	0.90
CN	0.74	1.53	1.02	1.19	1.38	0.75
SS	0.74	1.26	1.02	1.18	1.38	0.94

[1] Briggs, Wen, and Rose [Ref.28] tested a copper rectangular shaped finned tube with the following geometry; root diameter, D_r, of 12.7mm; inside diameter, D_i, of 9.82mm; fin height of 1.59mm; fin spacing of 1.5mm; fin thickness of 0.5mm. The values were taken directly from Table 1 of [Ref. 28].

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Steam condensation data were obtained for rectangular shaped finned tubes (D_r=13.88mm), deep radiussed root finned tubes (D_r=13.88mm), and shallow radiussed root finned tubes (D_r=14.38mm) made of copper, aluminum, copper nickel (90/10) and stainless steel (316) under both vacuum and atmospheric conditions. All tubes had a fin thickness of 1.0mm, fin spacing of 1.5mm and outer diameter (D_o)of 15.88mm. Based upon these measurements, the following conclusions are made:

1. Reliable baseline data have been obtained for finned tubes of copper, aluminum, copper nickel (90/10) and stainless steel (316).

2. For finned tubes, the thermal conductivity of the fin wall material had a significant effect on the condensation heat transfer coefficient. In fact, for the case of stainless steel, with it's poor thermal conductivity, a finned tube can perform worse than a smooth tube.

3. In going from a rectangular shaped fin to a radiussed root fin of the same root diameter, the condensation heat transfer coefficient decreased. This effect was more pronounced for high conductivity materials, and no notable change was observed for stainless steel tubes.

4. For rectangular shaped fins, the experimentally determined heat transfer enhancement ratio for copper at atmospheric pressure was found to be larger than that predicted by Beatty and Katz [Ref. 1] and by a modified version (to include fin efficiency) of Rose [Ref. 8]. For the other materials tested, as the thermal conductivity decreased, the data fell below the Beatty and Katz model and approached closer to the Rose

model. Under vacuum conditions, the data for all four materials were in much closer agreement to the Rose model and significantly below Beatty and Katz.

5. For a radiussed root finned tube, the experimentally determined heat transfer enhancement ratio for all tubes under both atmospheric and vacuum conditions was significantly less than predicted by the Rose model as modified to include a radiussed root fin geometry. Additional experimental data are required to determine better empirical constants that are utilized in the Rose model.

B. RECOMMENDATIONS

1. Retest each tube to obtain additional data in order to determine the empirical constants used in the Rose model [Ref. 8].

2. Manufacture new tubes with the same root diameter (13.88mm), tube materials and dimensions, but with a larger fin height of 2.0mm. After testing each tube, reduce the tube height for the next set by milling 0.25mm off. Continue this process down to a new fin height that is half the fin spacing.

3. Manufacture new tubes with a fin height of 2.0mm but change the fin spacing to 1.0mm. After each data test set mill 0.25mm off the fin height down to a new height of 0.5mm.

4. Manufacture new tubes with a fin height of 2.0mm and fin spacing of 1.5mm but change the fin thickness to 0.5mm. After each data set mill 0.25mm off the fin height down to a new fin height of 0.75mm.

5. Manufacture smooth tubes of aluminum, copper nickel (90/10) and stainless steel (316) for comparison with the smooth copper tube to determine the effect of the tube wall thermal conductivity on the leading coefficient (Ci) and the alpha (α) for determining the enhancement of the corresponding finned tubes.

6. Examine the Rose model [Ref. 8] in closer detail in order to refine the assumptions made and increase its validity.

7. Recalibrate and verify the operation of each measuring device in the system apparatus. While the system is disassembled, check and align the test section to ensure horizontal orientation.

8. Modify the apparatus by installing a pressure regulator for the auxiliary condenser cooling water.

9. Install a bi-metallic thermocouple and a control operated valve in the coolant water sump to maintain a constant temperature of the coolant entering the test tube.

10. Install a digital voltmeter to monitor the emf signal from the electrical switchboard to the data acquisition unit.

11. Provide removal lagging pads for the boiler and the test section to reduce the influence of the environment.

LIST OF REFERENCES

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APPENDIX A. DATA COLLECTION LISTING

The program DRPALL, which was used to collect and reprocess all data, is listed in this Appendix.

```
1000! DRPALL
1001! COMPLETE REVISION JULY 1993 (MEMORY)
1006! MODIFIED:  SEP 1992 (O'KEEFE)
1007! MODIFIED:  JAN 1993 (LONG)
1009! MODIFIED:  JUNE 1993 (COBB)
1010! TO BE USED WITH NON-INSTRUMENTED TUBES ONLY
1011! TAKES DATA IN THE FORMAT OF SWENSEN/O'KEEFE/LONG/COBB
1012! CAN REPROCESS ANY NON-INSTRUMENTED DATA
1013!
1014! THIS PROGRAM WAS USED TO COLLECT ALL THE NON-
1015! INSTRUMENTED DATA TAKEN BY LONG (JAN-JUN 1993) FOR TITANIUM TUBES
1017! AND THE FINNED TUBE DATA (RECTANGULAR AND FILLET RADIUS) OF COBB (JUN-SEPT
 1993)
1018!    MEANING OF ALL FLAGS IN PROGRAM
1019!
1020!    IFT:   FLUID TYPE
1021!    ISO:   OPTION WITHIN PROGRAM
1022!    IM:    INPUT MODE
1023!    IWIL:  VALUE OF C1 USED
1024!    IFG:   FINNED OR SMOOTH
1025!    INN:   INSERT TYPE
1026!    IWT:   LOOP NO. WITHIN PROGRAM
1027!    IWTH:  ALTERNATIVE CONDENSER TUBES
1028!    IMC:   TUBE MATERIAL
1029!    ITDS:  TUBE DIAMETER
1030!    IPC:   PRESSURE CONDITION
1031!    INF:   DIMENSIONLESS FILE REQUIRED
1032!    IPF:   PLOT FILE REQUIRED
1033!    IOV:   OUTPUT REQUIRED
1034!    IHI:   INSIDE HTC CORRELATION
1035!    IOC:   OUTSIDE HTC THEORY/CORRELATION
1036   COM /Cc/ C(7)
1037   COM /Cc55/ T55(5)
1038   COM /Cc56/ T56(5)
1039   COM /Cc57/ T57(5)
1040   COM /Cc58/ T58(5)
1041   COM /Fld/ Ift,Istu
1042   DIM Emf(20),Tw(6)
1043   COM /Pr/ Qpa(42),Tfm(42),Tfmr,Ipc,Qpr
1044   COM /Wil/ Nrun,Itm,Iwth,Imc,Ife,Ijob,Iwd,Ifg,Ipco,Ifto,Iwil,Ihi,Ioc,Inam,K
cu,Rexp,Rm,Ax
1045   COM /Geom/ D1,D2,Di,Do,L,L1,L2
1046   COM /Fric/ Istuo,Inn,Ityp,Vw,Inamo,Imco,Itds
1047   DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1048   DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1049   READ C(*)
1050   DATA 273.15,2.5943E-2,-7.2671E-7,3.2941E-11,-9.7719E-16,9.7121E-20
1051   READ T55(*)
```

```
1052 DATA 273.15,2.5878E-2,-5.9853E-7,-3.1242E-11,1.3275E-14,-1.0198E-18
1053 READ T56(*)
1054 DATA 273.15,2.5923E-2,-7.3933E-7,2.8625E-11,1.9717E-15,-2.2486E-19
1055 READ T57(*)
1056 DATA 273.15,2.5931E-2,-7.5232E-7,4.0657E-11,-1.2791E-15,6.4402E-20
1057 READ T58(*)
1058 Or=.015875     ! Outside diameter of the outlet end
1059 Dssp=.1524     ! Inside diameter of stainless steel test section
1060 Ax=PI*Dssp^2/4
1061 Alp2=0.
1062 L=.13335       ! Condensing length
1063 L1=.060325     ! Inlet end "fin length"
1064 L2=.034925     ! Outlet end "fin length"
1065 PRINTER IS 1
1066 BEEP
1067 PRINT USING "4X,""Select option:"""
1069 PRINT USING "6X,"" 0 Take data or re-process previous data"""
1084 PRINT USING "6X,"" 1 Print raw data"""
1090 PRINT USING "6X,"" 2 WILSON Analysys"""
1093 PRINT USING "6X,"" 3 MODIFY"""
1096 PRINT USING "6X,"" 4 PURGE"""
1102 PRINT USING "6X,"" 5 RENAME"""
1103 PRINT USING "6X,"" 6 MERGE FILES"""
1104 PRINT USING "6X,"" 7 X Y PLOT DATA OUTPUT"""
1106 INPUT Iso
1108 Iso=Iso+1
1111 IF Iso>1 THEN 3094
1112 BEEP
1115 INPUT "SELECT FLUID (0=WATER, 1=R-113, 2=EG)",Ift
1116 Ifto=Ift
1117 BEEP
1118 Ijob=0
1119 INPUT "ENTER INPUT MODE (0=3054A,1=FILE)",Im
1120 Im=Im+1
1123 BEEP
1124 IF Im=1 THEN
1126    INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1129    OUTPUT 709;"TD";Date$
1132    OUTPUT 709;"TD"
1133    ENTER 709;Date$
1135 END IF
1136 IF Ijob=1 THEN
1138    BEEP
1141    INPUT "SKIP PAGE AND HIT ENTER",Ok
1144 END IF
1145 PRINTER IS 701
1146 IF Im=1 THEN
1148    ENTER 709;Date$
```

```
1150     PRINT "           Month, date and time :";Date$
1151  END IF
1153  PRINT
1156  PRINT USING "10X,""NOTE: Program name : DRPALL"""
1171  IF Ijob=1 THEN 1189
1174  BEEP
1186  INPUT "SELECT (Ci:0=FIND,1=STORED Ci)",Iwil
1189  IF Im=1 THEN
1192     BEEP
1195     INPUT "GIVE A NAME FOR THE RAW DATA FILE",D_file$
1198     PRINT USING "16X,""File name    : "",14A";D_file$
1201     CREATE BDAT D_file$,30
1204     ASSIGN @File TO D_file$
1207     BEEP
1210     INPUT "ENTER GEOMETRY CODE (1=FINNED,0=PLAIN)",Ifg
1211     Inn=0
1212     PRINTER IS 1
1215     BEEP
1217     PRINT "   ENTER INSERT TYPE:"
1218     PRINT "      0=NONE (DEFAULT)"
1219     PRINT "      1=TWISTED TAPE"
1220     PRINT "      2=WIRE WRAP"
1221     PRINT "      3=HEATEX"
1222     INPUT Inn
1225     OUTPUT @File:Ifg,Inn
1227     Iwt=0  ! FOR UNINSTRUMENTED TUBE
1228     Fh=0
1231     Fp=0
1234     Fw=0
1235     Istu=0
1236     Istuo=Istu
1238     IF Ifg=0 THEN 1241
1239     INPUT "FIN PITCH, HEIGHT AND WIDTH IN MM, Fp,Fh,Fw",Fp,Fh,Fw
1241     OUTPUT @File;Iwt,Fp,Fw,Fh
1242  ELSE
1249     BEEP
1250     PRINTER IS 1
1252     PRINT "  STUDENT'S DATA TO BE REPROCESSED:"
1253     PRINT "  0=SWENSEN/O'KEEFE/LONG/COBB (DEFAULT)"
1255     PRINT "  1=VAN PETTEN/MITROU/COUMES/GUTTENDORF"
1256     INPUT Istu
1257     Istuo=Istu
1258     BEEP
1259     PRINT
1260     IF Istu=1 THEN
1261        PRINT " STUDENT NAME:"
1262        PRINT " 0=VAN PETTEN"
1263        PRINT " 1=MITROU"
```

```
1264        PRINT " 2=COUMES"
1265        PRINT " 3=GUTTENDORF"
1266     ELSE
1267        PRINT " 4=SWENSEN"
1268        PRINT " 5=O'KEEFE"
1269        PRINT " 6=LONG"
1270        PRINT " 7=COBB"
1271     END IF
1272     INPUT Inam
1273     Inamo=Inam
1277     BEEP
1278     INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D_file$
1279     PRINTER IS 701
1280     IF Inam=0 THEN PRINT USING "16X,""Data taken by                 : VAN PETT
EN"""
1281     IF Inam=1 THEN PRINT USING "16X,""Data taken by                 : MITROU""
"
1282     IF Inam=2 THEN PRINT USING "16X,""Data taken by                 : COUMES""
"
1283     IF Inam=3 THEN PRINT USING "16X,""Data taken by                 : GUTTENDO
RF"""
1284     IF Inam=4 THEN PRINT USING "16X,""Data taken by                 : SWENSEN"
""
1285     IF Inam=5 THEN PRINT USING "16X,""Data taken by                 : O'KEEFE"
""
1286     IF Inam=6 THEN PRINT USING "16X,""Data taken by                 : LONG"""
1287     IF Inam=7 THEN PRINT USING "16X,""Data taken by                 : COBB"""
1288     PRINT USING "16X,""This analysis done on file : "",10A":D_file$
1289     PRINTER IS 1
1290     BEEP
1291     INPUT "ENTER NUMBER OF DATA SETS STORED",Nrun
1292     ASSIGN @File TO D_file$
1293     ENTER @File;Ifg,Inn
1294     IF Istu=0 THEN
1295        ENTER @File;Iwt,Fp,Fw,Fh
1296     ELSE
1297        IF Ifg=0 THEN ENTER @File;Iwt
1298        IF Ifg=1 THEN ENTER @File;Fp,Fw,Fh
1299     END IF
1300  END IF
1301  IF Istu=1 AND Inn=1 THEN Inn=2
1303  IF Ijob=1 THEN 1537
1304  IF Ift<>0 THEN 1349
1305  BEEP
1306  PRINTER IS 1
1307  PRINT USING "4X,""Select tube type:"""
1328  PRINT USING "6X,""0 SMOOTH TUBE"""
1329  PRINT USING "6X,""1 FINNED TUBE (RECTANGULAR)"""
```

```
1330  PRINT USING "6X,""2 WIRE-WRAPPED SMOOTH TUBE"""
1331  PRINT USING "6X,""3 LPD KORODENSE TUBE"""
1332  PRINT USING "6X,""4 WIRE-WRAPPED LPD KORODENSE TUBE"""
1333  PRINT USING "6X,""5 MHT KORODENSE TUBE"""
1334  PRINT USING "6X,""6 WIRE-WRAPPED MHT KORODENSE TUBE"""
1336  PRINT USING "6X,""7 FINNED TUBE (SHALLOW FILLET)"""
1337  PRINT USING "6X,""8 FINNED TUBE (DEEP FILLET)"""
1338  INPUT Ityp
1339  PRINTER IS 701
1340  BEEP
1341  PRINTER IS 1
1342  PRINT USING "4X,""Select Material Code:"""
1343  PRINT USING "6X,""0 COPPER     1 STAINLESS STEEL"""
1344  PRINT USING "6X,""2 ALUMINUM  3 90:10 CU/NI"""
1345  PRINT USING "6X,""4 TITANIUM """
1346  INPUT Imc
1347  Imco=Imc
1349  PRINTER IS 1
1350  BEEP
1351  Itds=1
1353  PRINT USING "4X,""SELECT TUBE DIA TYPE:"""
1357  PRINT USING "6X,""0  SMALL"""
1360  PRINT USING "6X,""1  MEDIUM (DEFAULT)"""
1363  PRINT USING "6X,""2  LARGE"""
1364  PRINT USING "6X,""3  SMALL (COBB)"""
1367  PRINT USING "6X,""4  OTHER (LPD/MHT)"""
1368  INPUT Itds
1372  IF (Ityp=0 OR Ityp=1 OR Ityp=2) AND Imc=0 THEN
1375  IF Itds=0 THEN
1375     Di=.009525
1377     Do=.0127
1378  END IF
1379  IF Itds=1 THEN
1380     Di=.0127
1381     Do=.01905
1383  END IF
1384  IF Itds=2 THEN
1385     Di=.0127
1386     Do=.025
1387  END IF
1388  IF Itds=3 THEN
1389     Di=.0127
1390!    Do=.01388     !DEEP DEPTH
1391     Do=.01438     !SHALLOW DEPTH
1393  END IF
1394  IF Itds=4 THEN
1395     PRINT USING "6X,""ERROR - NO COPPER LPD/MHT"""
1396  END IF
```

```
1397  END IF
1398  IF (Ityp=1 OR Ityp=8) AND Itds=3 THEN
1399     Di=.0127
1400     Do=.01383
1402  END IF
1403  IF Ityp=7 AND Itds=3 THEN
1404     Di=.0127
1405     Do=.01438
1406  END IF
1408  IF (Ityp=3 OR Ityp=4) AND Imc=4 THEN
1409     Di=.01347
1410     Do=.01585
1411  END IF
1457  IF (Ityp=0 OR Ityp=2) AND Imc=4 THEN
1458     Do=.01585
1459     Di=.01336
1460  END IF
1461  IF (Ityp=5 OR Ityp=6) AND Imc=4 THEN
1462     Do=.01507
1463     Di=.01353
1465  END IF
1467  D1=.01905
1468  D2=.01585
1478  IF Itds=3 OR Itds=4 THEN D1=.01585
1484  IF (Ityp=0 OR Ityp=2) AND Imc=4 THEN D1=.01585
1492!  THERMAL CONDUCTIVITIES TAKEN FROM "THERMOPHYSICAL PROPERTIES OF MATTER"
1493!  THE TPRC DATA SERIES - VOLUME 1
1494  IF Imc=0 THEN Kcu=390.8
1495  IF Imc=1 THEN Kcu=14.3
1496  IF Imc=2 THEN Kcu=231.8
1497  IF Imc=3 THEN Kcu=55.3
1498  IF Imc=4 THEN Kcu=18.9
1499  Rm=Do*LOG(Do/Di)/(2*Kcu) ! Wall resistance based on outside area
1501  BEEP
1504  INPUT "ENTER PRESSURE CONDITION (0=V,1=A)",Ipc
1507  Ipco=Ipc
1508  Inf=0
1510  BEEP
1537  Ife=1
1538  PRINTER IS 701
1543  PRINT USING "16X,""This analysis includes end-fin effect"""
1546  PRINT USING "16X,""Thermal conductivity      = "",3D.D,"" (W/m.K)""";Kcu
1549  PRINT USING "16X,""Inside diameter, Di       = "",DD.DD,"" (mm)""";Di*1000
1552  PRINT USING "16X,""Outside diameter, Do      = "",DD.DD,"" (mm)""";Do*1000
1556  Ihi=0
1557  PRINTER IS 1
1558  PRINT "     SELECT INSIDE CORRELATION:"
1559  PRINT "         0=SIEDER-TATE (DEFAULT)"
```

```
1560  PRINT "         1=SLEICHER-ROUSE"
1561  PRINT "         2=PETUKHOV-POPOV"
1562  INPUT Ihi
1563  IF Ihi=0 THEN
1564     BEEP
1566     INPUT "    SELECT REYNOLDS EXPONENT",Rexp
1567  END IF
1568  Ioc=0
1569  BEEP
1570  PRINT
1571  PRINT "    SELECT OUTSIDE THEORY/CORRELATION FOR WILSON ANALYSIS:"
1572  PRINT "         0=NUSSELT THEORY (DEFAULT)"
1573  PRINT "         1=FUJII (1979) CORRELATION"
1574  INPUT Ioc
1575  BEEP
1576  Itm=1
1577  PRINT
1578  PRINT "    SELECT COOLANT TEMPERATURE RISE MEASUREMENT:"
1579  IF Istu=0 THEN PRINT "         0=SINGLE TEFLON T/C"
1580  PRINT "         1=QUARTZ THERMOMETER (DEFAULT)"
1581  PRINT "         2=10-JUNCTION THERMOPILE"
1582  INPUT Itm
1583  PRINTER IS 701
1584  IF Itm=0 THEN PRINT USING "16X,""This analysis uses the SINGLE TEFLON T/C
readings"""
1585  IF Itm=1 THEN PRINT USING "16X,""This analysis uses the QUARTZ THERMOMETER
 readings"""
1586  IF Itm=2 THEN PRINT USING "16X,""This analysis uses the 10-JUNCTION THERMO
PILE readings"""
1587  Iic=1 ! FOR MODIFIED WILSON
1588  IF Ihi=0 AND Inn=0 THEN Ci=.027
1591  IF Ihi=0 AND Inn=2 THEN Ci=.05
1592  IF Ihi=0 AND Inn=3 THEN Ci=.07
1594  IF Ihi=1 OR Ihi=2 THEN
1595     IF Inn=0 THEN Ci=1.0
1597     IF Inn=2 THEN Ci=2.0
1598     IF Inn=3 THEN Ci=2.5
1599  END IF
1601  IF Iwil=1 THEN
1602     BEEP
1603     INPUT "ENTER Ci IF DIFFERENT FROM STORED VALUE",Ci
1604  END IF
1605  PRINTER IS 701
1606  IF Ihi=0 THEN PRINT USING "16X,""Modified Sieder-Tate coefficient   = "",Z
.4D";Ci
1607  IF Ihi=0 THEN PRINT USING "16X,""Chosen Reynolds No. exponent       = "",D
.DD";Rexp
1608  IF Ihi=1 THEN PRINT USING "16X,""Modified Sleicher-Rouse coefficient   = "
```

```
",Z.4D";Ci
1609  IF Ihi=2 THEN PRINT USING "16X,""Modified Petukhov-Popov coefficient    = "
",Z.4D";Ci
1610  IF Inn=0 THEN PRINT USING "16X,""Using no insert inside tube"""
1611  IF Inn=2 THEN PRINT USING "16X,""Using wire wrap insert inside tube"""
1612  IF Inn=3 THEN PRINT USING "16X,""Using HEATEX insert inside tube"""
1620  IF Iic=1 THEN Ac=0.
1621  BEEP
1622  IF Ijob=1 THEN 1648
1623  PRINTER IS 1
1624! INPUT "NAME FOR A TEMPORARY PLOT FILE (TO BE PURGED)",P_file$
1625  P_file$="DUMMY"
1626  BEEP
1634  CREATE BDAT P_file$,30
1644  ASSIGN @Filep TO P_file$
1648  IF Ijob=1 THEN
1651     Iov=1
1654     GOTO 1667
1657  END IF
1660  BEEP
1661  INPUT "SELECT OUTPUT (0=SHORT, 1=LONG)",Iov
1666  Iov=Iov+1
1667  PRINTER IS 701
1672  IF Ityp=0 THEN PRINT USING "16X,""Tube Enhancement    : SMOOTH TUBE"""
1673  IF Ityp=1 THEN PRINT USING "16X,""Tube Enhancement    : RECTANGULAR FINNED
TUBE"""
1674  IF Ityp=2 THEN PRINT USING "16X,""Tube Enhancement    : WIRE-WRAPPED SMOOTH
 TUBE"""
1675  IF Ityp=3 THEN PRINT USING "16X,""Tube Enhancement    : LPD KORODENSE TUBE"
""
1678  IF Ityp=4 THEN PRINT USING "16X,""Tube Enhancement    : WIRE-WRAPPED LPD KO
RODENSE TUBE"""
1679  IF Ityp=5 THEN PRINT USING "16X,""Tube Enhancement    : MHT KORODENSE TUBE"
""
1680  IF Ityp=6 THEN PRINT USING "16X,""Tube Enhancement    : WIRE-WRAPPED MHT KO
RODENSE TUBE"""
1681  IF Ityp=7 THEN PRINT USING "16X,""Tube Enhancement    : SHALLOW FILLET FINN
ED TUBE"""
1682  IF Ityp=8 THEN PRINT USING "16X,""Tube Enhancement    : DEEP FILLET FINNED
TUBE"""
1683  BEEP
1684  IF Imc=0 THEN PRINT USING "16X,""Tube material       : COPPER"""
1685  IF Imc=1 THEN PRINT USING "16X,""Tube material       : STAINLESS-STEEL"""
1686  IF Imc=2 THEN PRINT USING "16X,""Tube material       : ALUMINUM"""
1687  IF Imc=3 THEN PRINT USING "16X,""Tube material       : 90/10 CU/NI"""
1688  IF Imc=4 THEN PRINT USING "16X,""Tube material       : TITANIUM"""
1689  IF Ipc=0 THEN PRINT USING "16X,""Pressure condition : VACUUM"""
1690  IF Ipc=1 THEN PRINT USING "16X,""Pressure condition : ATMOSPHERIC"""
```

```
1691  PRINT USING "16X,""Fin pitch, width, and height (mm): "",DD.DD,2X,Z.DD,2X,
Z.DD";Fp,Fw,Fh
1692  IF Iwil=0 AND Im=2 THEN
1693     Ijob=1
1694     Iwd=1
1696     CALL Wilson(Ci)
1699  END IF
1702  J=0
1712  IF Iov=1 THEN
1722     PRINT
1723     IF Ihi=1 THEN
1724        PRINT USING "10X,""Data  Vw      Uo          Ho         Qp        Tcf
   Ts     Rexp"""
1725        PRINT USING "10X,""  # (m/s)  (W/m^2-K)  (W/m^2-K)   (W/m^2)   (C)
  (C)  (S-R)"""
1726     ELSE
1728        PRINT USING "10X,""Data    Vw       Uo          Ho           Qp
    Tcf      Ts"""
1729        PRINT USING "10X,"" #     (m/s)   (W/m^2-K)    (W/m^2-K)   (W/m^2)
    (C)      (C)"""
1730     END IF
1740  END IF
1747  Zx=0
1750  Zx2=0
1753  Zxy=0
1756  Zy=0
1759  Sx=0
1762  Sy=0
1765  Sxs=0
1768  Sxy=0
1771  Go_on=1
1774 Repeat:!
1777  J=J+1
1780  IF Im=1 THEN
1783     BEEP
1786     INPUT "LIKE TO CHECK NG CONCENTRATION (1=Y,0=N)?",Ng
1789     IF J=1 THEN
1792        OUTPUT 709;"AR AF40 AL41 VRS"
1795        OUTPUT 709;"AS SA"
1798     END IF
1801     BEEP
1804     INPUT "ENTER FLOWMETER READING",Fm
1807     OUTPUT 709;"AR AF60 AL62 VRS"
1810     OUTPUT 709;"AS SA"
1813     ENTER 709;Etp
1816     OUTPUT 709;"AS SA"
1819     BEEP
1822     INPUT "CONNECT VOLTAGE LINE",Ok
```

```
1825    ENTER 709;Bvol
1828    BEEP
1831    INPUT "DISCONNECT VOLTAGE LINE",Ok
1834    IF Bvol<.1 THEN
1837       BEEP
1840       BEEP
1843       INPUT "INVALID VOLTAGE, TRY AGAIN!",Ok
1846       GOTO 1819
1849    END IF
1858    OUTPUT 709;"AS SA"
1861    ENTER 709;Bamp
1862    Etp=Etp*1.E+6
1863    OUTPUT 709;"AR AF40 AL47 VRS"
1874    Nn=7
1876    FOR I=0 TO Nn
1879       OUTPUT 709;"AS SA"
1885       Se=0
1888       FOR K=1 TO 10
1891          ENTER 709;E
1894          Se=Se+E
1897       NEXT K
1900       Emf(I)=ABS(Se/10)
1916       Emf(I)=Emf(I)*1.E+6
1918    NEXT I
1921    OUTPUT 709;"AS SA"
1924    OUTPUT 713;"T1R2E"
1927    WAIT 2
1930    ENTER 713;T11
1933    OUTPUT 713;"T2R2E"
1936    WAIT 2
1939    ENTER 713;T2
1942    OUTPUT 713;"T1R2E"
1945    WAIT 2
1948    ENTER 713;T12
1951    T1=(T11+T12)*.5
1954    OUTPUT 713;"T3R2E"
1960    BEEP
1970    INPUT "ENTER PRESSURE GAGE READING (Pga)",Pga
1971    Pvap1=Pga*6894.7 ! PSI TO Pa
1972    OUTPUT 709;"AR AF64 AL64 VRS"
1973    OUTPUT 709;"AS SA"    ! PRESSURE TRANSDUCER
1974    Ss=0
1975    FOR K=1 TO 20
1976       ENTER 709;Etran
1977       Ss=Ss+Etran
1978    NEXT K
1979    Ptran=ABS(Ss/20)
1980    BEEP
1981!   PRESSURE IN Pa FROM TRANSDUCER
1982    Pvap2=(-2.93604*Ptran+14.7827)*6894.7
1985 ELSE
1986    IF Istu=0 THEN
1989       ENTER @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
1990    ELSE
```

```
1992         ENTER @File;Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),F
m,T1,T2,Phg,Pwater
1994      END IF
1996      IF J=1 OR J=20 OR J=Nrun THEN
1997         Ng=1
1998      ELSE
1999         Ng=0
2000      END IF
2002   END IF
2003   IF Istu=0 THEN
2008      Tsteam1=FNTvsv57(Emf(0))
2009      Tsteam1=Tsteam1-273.15
2010      Tsteam2=FNTvsv56(Emf(1))
2011      Tsteam2=Tsteam2-273.15
2012      Tsteam=Tsteam1
2015      Troom=FNTvsv58(Emf(2))
2023      Troom=Troom-273.15
2038      Tcon=FNTvsv58(Emf(7))
2039      Tcon=Tcon-273.15
2042   ELSE
2043      Tsteam=FNTvsv(Emf(0))
2044      Troom=FNTvsv(Emf(3))
2045      Tcon=FNTvsv(Emf(4))
2046   END IF
2048   Psat=FNPvst(Tsteam)
2050   Rohg=13529-122*(Troom-26.85)/50
2053   Rowater=FNRhow(Troom)
2063   IF Istu=0 THEN
2081      Ptest1=Pvap1
2082      Ptest2=Pvap2
2083   ELSE
2084      Ptest2=(Phg*Rohg-Pwater*Rowater)*9.81/1000
2085   END IF
2087   Pks=Psat*1.E-3
2088   Pkp=Ptest2*1.E-3
2090   Pkt=Pks
2091   Ttran=FNTvsp(Ptest2)
2092!  PRINT Psat,Ptest2,Ttran,Tsteam
2098   Vst=FNVvst(Tsteam)
2104   Ppng=(Ptest2-Psat)/Ptest2
2121   Ppst=1-Ppng
2122   Mwv=18.016
2123   IF Ift=1 THEN Mwv=137    ! TO BE CORRECTED
2124   IF Ift=2 THEN Mwv=62
2125   Vfng=(Ptest2-Psat)/Ptest2
2126   Mfng=1/(1+(1/Vfng-1)*Mwv/28.97)
2127   Mfng=Mfng*100
2128   Vfng=Vfng*100
```

```
2131  BEEP
2134  IF Iov=2 THEN
2137     PRINT
2138!    RECORD TIME OF TAKING DATA
2139     IF Im=1 THEN
2140        OUTPUT 709;"TD"
2141        ENTER 709;Told$
2142     END IF
2144     PRINT USING "10X,""Data set number              = "",DD,4X,14A";J,Told$
2145     OUTPUT 709;"AR AF40 AL40 VRS"
2146     OUTPUT 709;"AS SA"
2149  END IF
2152  IF Iov=2 AND Ng=1 THEN
2155     IF Istu=0 THEN PRINT USING "10X,""   Psat     Ptran    Tsat     Ttran      N
6 %"""
2156     IF Istu=1 THEN PRINT USING "10X,""   Psat     Pman     Tsat     Tman       N
6 %"""
2158     PRINT USING "10X,""  (kPa)    (kPa)    (C)      (C)    Molal """
2161    PRINT USING "11X,5(M3D.D,2X)";Pks,Pkp,Tsteam,Ttran,Mfng
2164     PRINT
2167  END IF
2170  IF Mfng>.5 THEN
2173     BEEP
2176     IF Im=1 AND Ng=1 THEN
2179        BEEP
2182        PRINT
2185        PRINT USING "10X,""Energize the vacuum system """
2188        BEEP
2191        INPUT "OK TO ACCEPT THIS RUN (1=Y,0=N)?",Ok
2194        IF Ok=0 THEN
2197           BEEP
2200           DISP "NOTE: THIS DATA SET WILL BE DISCARDED!! "
2203           WAIT 5
2206           GOTO 1780
2209        END IF
2212     END IF
2215  END IF
2218  IF Im=1 THEN
2221     IF Fm<10 OR Fm>100 THEN
2224        Ifm=0
2227        BEEP
2230        INPUT "INCORRECT FM (1=ACCEPT,0=DELETE)",Ifm
2233        IF Ifm=0 THEN 1804
2236     END IF
2239  END IF
2242! ANALYSIS BEGINS
2243  IF Istu=0 THEN
2252     Ti1=FNTvsv58(Emf(3))
```

```
2272      To1=FNTvsv58(Emf(4))
2292      Ti1=Ti1-273.15
2312      To1=To1-273.15
2332      Tdel1=To1-Ti1
2352      Tdel2=T2-T1
2353      Etp1=Emf(3)+Etp/20.
2354      Dtde=2.5931E-2-1.50464E-6*Etp1+1.21701E-10*Etp1^2-5.1164E-15*Etp1^3+3.2
201E-19*Etp1^4
2355      Tris=Dtde*Etp/10.
2358      To3=Ti1+Tris
2359      IF Iov=2 THEN
2361         PRINT USING "1X,""   TIN1    TOUT1    TIN2    TOUT2    DELT1    DELT2
TPILE  """
2362         PRINT USING "1X,""   (SINGLE)         (QUARTZ) """
2364         PRINT USING "2X,7(3D.DD,2X)";Ti1,To1,T1,T2,Tdel1,Tdel2,Tris
2365      END IF
2367      Er1=ABS(Ti1-T1)
2369      PRINTER IS 1
2370      BEEP
2375      Er2=ABS((T2-T1)-(Tris))/(T2-T1)
2377      IF Er2>.05 AND Im=1 THEN
2378         BEEP
2379         PRINT "QCT AND T-PILE DIFFER BY MORE THAN 5%"
2380         Ok2=1
2381         IF Ok2=0 AND Er2>.05 AND Im=1 THEN 1780
2382      END IF
2383      PRINTER IS 701
2384   ELSE
2385      Tsteam=FNTvsv(Emf(0))
2387      Ti1=FNTvsv(Emf(2))
2388      Grad=FNGrad((T1+T2)*.5)
2389      To3=Ti1+ABS(Etp)/(10*Grad)*1.E+6
2392   END IF
2393   IF Istu=0 AND Itm=0 THEN
2394      Tcin=Ti1
2395      Tcout=To1
2396   END IF
2397   IF Itm=1 THEN
2398      Tcin=T1
2399      Tcout=T2
2400   END IF
2401   IF Itm=2 THEN
2402      Tcin=Ti1
2403      Tcout=To3
2404   END IF
2405   Tavg=(Tcin+Tcout)*.5
2406   Trise=Tcout-Tcin
2407!  PRINT Trise
```

```
2414  Ift=0
2415  Cpw=FNCpw(Tavg)
2416  Rhow=FNRhow(Tavg)
2417  Kw=FNKw(Tavg)
2418  Muwa=FNMuw(Tavg)
2419  Prw=FNPrw(Tavg)
2420  Ift=Ifto
2422  IF Istu=0 THEN
2423     Mdt=(6.7409*Fm+13.027)/1000.
2424     Md=Mdt*(1.0365-1.96644E-3*Tcin+5.252E-6*Tcin^2)/1.0037
2425  ELSE
2426     Mdt=1.04805E-2+6.80932E-3*Fm
2427     Md=Mdt*(1.0365-1.96644E-3*Tcin+5.252E-6*Tcin^2)/.995434
2428  END IF
2429  Vf=Md/Rhow
2430  Vw=Vf/(PI*Di^2/4)
2431  Tcor=FNTfric(Trise)
2432  Trise=Tcor
2433  Tcout=Tcin+Trise
2434  Lmtd=Trise/LOG((Tsteam-Tcin)/(Tsteam-Tcout))
2447  Q=Md*Cpw*Trise
2448  Qp=Q/(PI*Do*L)
2449  Uo=Qp/Lmtd
2451! PRINT Trise,Q,Do,L,Qp,Lmtd,Uo,Vw
2452  Rei=Rhow*Vw*Di/Muwa ! ASSUMED SAME FOR KORODENSE
2453  Ift=0
2455  Fe1=0.
2456  Fe2=0.
2457  Cf=1.
2458  Prwf=Prw
2459  Reif=Rei
2461  IF Ihi=0 THEN
2463     Omega=Rei^Rexp*Prw^.3333*Cf
2465  END IF
2466  IF Ihi=1 THEN
2467     Sra=.88-(.24/(4.+Prwf))
2468     Srb=.333333+.5*EXP(-.6*Prwf)
2470     Omega=(5.+.015*Reif^Sra*Prwf^Srb)
2471  END IF
2472  IF Ihi=2 THEN
2473     Epsi=(1.82*LGT(Rei)-1.64)^(-2)
2474     Ppk1=1.+3.4*Epsi
2475     Ppk2=11.7+1.8*Prw^(-1/3)
2476     Pp1=(Epsi/8)*Rei*Prw
2477     Pp2=(Ppk1+Ppk2*(Epsi/8)^.5*(Prw^.6666-1))
2478     Omega=Pp1/Pp2
2479  END IF
2481  Hi=Kw/Di*Ci*Omega
```

```
2482  IF Ife=0 THEN GOTO 2491
2483  P1=PI*(Di+D1)
2484  A1=(D1-Di)*PI*(D1+Di)*.5
2485  M1=(Hi*P1/(Kcu*A1))^.5
2486  P2=PI*(Di+D2)
2487  A2=(D2-Di)*PI*(Di+D2)*.5
2488  M2=(Hi*P2/(Kcu*A2))^.5
2489  Fe1=FNTanh(M1*L1)/(M1*L1)
2490  Fe2=FNTanh(M2*L2)/(M2*L2)
2491  Dt=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
2492  IF Ihi=0 THEN
2494     Cfc=(Muwa/FNMuw(Tavg+Dt))^.14
2495     IF ABS((Cfc-Cf)/Cfc)>.001 THEN
2497        Cf=(Cf+Cfc)*.5
2500        GOTO 2461
2501     END IF
2503  END IF
2504  IF Ihi=1 THEN
2505     Prwfc=FNPrw(Tavg+Dt)
2506     Reifc=Vw*Di*FNRhow(Tavg+Dt)/FNMuw(Tavg+Dt)
2507     IF ABS((Prwfc-Prwf)/Prwfc)>.001 OR ABS((Reifc-Reif)/Reifc)>.001 THEN
2508        Prwf=(Prwfc+Prwf)/2.
2509        Reif=(Reifc+Reif)/2.
2510        GOTO 2461
2511     END IF
2513  END IF
2516  Ift=Ifto
2521  Ho=1/(1/Uo-Do*L/(Di*(L+L1*Fe1+L2*Fe2)*Hi)-Rm)
2522  Tcf=Qp/Ho
2525  Cpsc=FNCpw((Tcon+Tsteam)*.5)
2526  Hfg=FNHfg(Tsteam)
2527  Two=Tsteam-Qp/Ho
2528  Tfilm=Tsteam/3+Two*2/3
2530  Kf=FNKw(Tfilm)
2533  Rhof=FNRhow(Tfilm)
2536  Muf=FNMuw(Tfilm)
2537  Hfgp=FNHfg(Tsteam)+.68*FNCpw(Tfilm)*(Tsteam-Two)
2539! Hpq=.651*Kf*(Rhof^2*9.81*Hfgp/(Muf*Do*Qp))^.3333
2541  Hnuss=.728*(Kf^3*9.81*Hfgp*Rhof^2/(Muf*Do*(Tsteam-Two)))^.25
2542  Alp1=.728*Ho/Hnuss
2548  Tfm(J-1)=Tfilm
2551  Qpa(J-1)=Qp
2554  Y=Hpq*Qp^.3333
2557  X=Qp
2560  Sx=Sx+X
2563  Sy=Sy+Y
2566  Sxs=Sxs+X^2
2569  Sxy=Sxy+X*Y
```

```
2572  Q1=500
2575  Qloss=Q1/(100-25)*(Tsteam-Troom)  ! TO BE MODIFIED
2584  Mdv=0
2587  Bp=(Bvol*100)^2/5.76
2590  Hsc=Cpsc*(Tsteam-Tcon)
2593  Mdvc=((Bp-Qloss)-Mdv*Hsc)/Hfg
2596  IF ABS((Mdv-Mdvc)/Mdvc)>.01 THEN
2599     Mdv=(Mdv+Mdvc)*.5
2602     GOTO 2593
2605  END IF
2608  Mdv=(Mdv+Mdvc)*.5
2611  Vg=FNVvst(Tsteam)
2614  Vv=Mdv*Vg/Ax
2620  F=(9.81*Do*Muf*Hfg)/(Vv^2*Kf*(Tsteam-Two))
2623  Nu=Ho*Do/Kf
2626  Ret=Vv*Rhof*Do/Muf
2629  Nr=Nu/Ret^.5
2630  Hfuj=.96*(9.81*Hfgp/Tcf)^.2*Kf^.8*Vv^.1*Rhof^.5/(Do*Muf)^.3
2635  IF Iov=2 THEN
2645     PRINT
2647     PRINT USING "5X,"" Vw       Rei          Hi           Uo           Hfuj(DT)
    Hnu(DT)"""
2650     PRINT USING "5X,Z.DD,1X,3(MZ.3DE,1X),3X,2(MZ.3DE,3X)";Vw,Rei,Hi,Uo,Hfuj
,Hnuss
2651     PRINT
2653     PRINT USING "5X,"" Vv       Ho          q           Tcf        Tfilm       T
stm"""
2655     PRINT USING "5X,Z.DD,1X,5(MZ.3DE,1X)";Vv,Ho,Qp,Tcf,Tfilm,Tsteam
2656     PRINT
2658  END IF
2659  IF Iov=1 THEN
2660    IF Ihi=1 THEN
2661     PRINT USING "11X,DD,2X,Z.DD,1X,3(MD.3DE,1X),2(3D.DD,1X),D.DDD";J,Vw,Uo,
Ho,Qp,Tcf,Tsteam,Sra
2662     PRINT USING "5X,"" Tfilm """;Tfilm
2664    ELSE
2668   PRINT USING "11X,DD,4X,Z.DD,2X,2(MD.3DE,2X),Z.3DE,3X,3D.DD,2X,3D.DD";J,Vw
,Uo,Ho,Qp,Tcf,Tsteam
2671    END IF
2674  END IF
2675  IF Im=2 THEN
2684     IF (Iwil=0 AND Ijob=1) OR Iwil>0 THEN OUTPUT @Filep;Qp,Ho
2694  END IF
2707  BEEP
2708  IF Im=1 THEN
2709     IF (Iwil=0 AND Ijob=1) OR Iwil=1 THEN OUTPUT @Filep;Qp,Ho
2711     INPUT "CHANGE TCOOL RISE? 1=Y, 2=N",Itr
2712     IF Itr=1 THEN GOTO 2384
```

```
2713      BEEP
2715      INPUT "OK TO STORE THIS DATA SET (1=Y,0=N)?",Oks
2716      IF Oks=1 THEN
2725         OUTPUT @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
2735         Alp2=Alp1+Alp2
2749      ELSE
2752         J=J-1
2755      END IF
2758      BEEP
2761      INPUT "WILL THERE BE ANOTHER RUN (1=Y,0=N)?",Go_on
2764      Nrun=J
2767      IF Go_on<>0 THEN Repeat
2770   ELSE
2773      IF J<Nrun THEN Repeat
2776   END IF
2779   IF Ijob=1 THEN 2809
2782   IF Iwil=0 THEN
2785      ASSIGN @File TO *
2788      Ijob=1
2791      Iwd=1
2794!     CALL Wilson(Ci)
2797      Im=2
2800      ASSIGN @File TO D_file$
2803      GOTO 1136
2806   END IF
2809   IF Ifg=0 THEN
2812      PRINT
2815      S1=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxs-Sx^2)
2818      Ac=(Sy-S1*Sx)/Nrun
2822      PRINT USING "10X,""Least-Squares Line for Ho vs q curve:"""
2824      PRINT USING "10X,""  Slope      = "",MD.4DE";S1
2827      PRINT USING "10X,""  Intercept  = "",MD.4DE";Ac
2830   END IF
2833   BEEP
2843!  INPUT "ENTER SAME TEMPORARY PLOT FILE NAME",Fplot$
2853   ASSIGN @Filep TO P_file$
2863   FOR I=1 TO Nrun
2873      ENTER @Filep;Qp,Ho
2883      Xc=LOG(Qp/Ho)
2884      Yc=LOG(Qp)
2885      Zx=Zx+Xc
2886      Zx2=Zx2+Xc^2
2887      Zxy=Zxy+Xc*Yc
2888      Zy=Zy+Yc
2889   NEXT I
2890   Bb=.75
2891   Aa=EXP((Zy-Bb*Zx)/Nrun)
2892   PRINT
```

```
2893  PRINT USING "10X,""Least-squares line for q = a*delta-T^b"""
2894  PRINT USING "12X,""a = "",MZ.4DE";Aa
2895  PRINT USING "12X,""b = "",MZ.4DE";Bb
2896  IF Ift=0 THEN
2897     IF Ipc=0 THEN
2898        Qps=2.5E+5
2899        IF Iic=0 THEN Hop=9326
2902        IF Iic=1 THEN Hop=10165*(.01905/Do)^.33333
2905     END IF
2908     IF Ipc=1 THEN
2911        Qps=7.5E+5
2914        IF Iic=0 THEN Hop=7176
2917        IF Iic=1 THEN Hop=7569*(.01905/Do)^.33333
2920     END IF
2923     Hos=Aa^(1/Bb)*Qps^((Bb-1)/Bb)
2926     IF Ipc=0 THEN Aas=2.32E+4
2929     IF Ipc=1 THEN Aas=2.59E+4
2930     Alpsm=.876   !SWENSEN DATA
2931     IF Iwil=0 THEN GOTO 2959
2933     Enrat=Alp2/Alpsm
2934     Enr=Hos/Hop
2935!    Enr=Aa/Aas
2938     PRINT
2941!    PRINT USING "10X,""Values computed at q = "",Z.DD,"" (MW/m^2):""";Qps/1
.E+6
2944!    PRINT USING "12X,""Heat-transfer coefficient = "",DDD.DDD,"" (kW/m^2.K)
""";Hos/1000
2947     PRINT USING "12X,""Enhancement ratio (Del-T) =  "",2D.3D";Enrat
2950!    PRINT USING "10X,""Enhancement ratio at constant Delta-T  = "",DD.DD";E
nr
2953!    PRINT USING "10X,""Enhancement ratio at constant q        = "",DD.DD";E
nr^1.3333
2956  ELSE
2959     PRINT
2962     IF Ift=1 THEN
2965        Aas=2687.2  ! ZEBROWSKI (V = 0.4 m/s)
2968        Aas=2557.0*(.01905/Do)^.33333  ! VAN PETTEN (V = 0.25 m/s)
2971     END IF
2974     IF Ift=2 THEN Aas=9269.7*(.01905/Do)^.33333
2977     Edt=Aa/Aas
2980     Eq=Edt^(4/3)
2983!    PRINT USING "10X,""Enhancement (q)      = "",DD.3D";Eq
2986!    PRINT USING "10X,""Enhancement (Del-T) = "",DD.3D";Edt
2989  END IF
2992! IF Im=1 THEN
2995     BEEP
2998     PRINT
3001     PRINT USING "10X,""NOTE: "",ZZ,"" data points were stored in file "",10
```

```
A";J,D_file$
3004! END IF
3007  BEEP
3013  PRINT
3016  PRINT USING "10X,""NOTE: "",ZZ,"" X-Y pairs were stored in data file "",10
A";J,Plot$
3031  BEEP
3073  ASSIGN @File TO *
3079  ASSIGN @Filep TO *
3080  PURGE "DUMMY"
3094  IF Iso=2 THEN CALL Raw
3100  IF Iso=3 THEN CALL Wilson(Ci)
3103  IF Iso=4 THEN CALL Modify
3106  IF Iso=5 THEN CALL Purg
3112  IF Iso=6 THEN CALL Renam
3113  IF Iso=7 THEN CALL Mergefile
3114  IF Iso=8 THEN CALL Xyoutput
3116  END
3118  DEF FNPvst(Tc)
3121  COM /Fld/ Ift,Istu
3124  DIM K(8)
3127  IF Ift=0 THEN
3130     DATA -7.691234564,-26.08023696,-168.1706546,64.23795504,-118.9646225
3133     DATA 4.16711732,20.9750676,1.E9,6
3136     READ K(*)
3139     T=(Tc+273.15)/647.3
3142     Sum=0
3145     FOR N=0 TO 4
3148        Sum=Sum+K(N)*(1-T)^(N+1)
3151     NEXT N
3154     Br=Sum/(T*(1+K(5)*(1-T)+K(6)*(1-T)^2))-(1-T)/(K(7)*(1-T)^2+K(8))
3157     Pr=EXP(Br)
3160     P=22120000*Pr
3163  END IF
3166  IF Ift=1 THEN
3169     Tf=Tc*1.8+32+459.6
3172     P=10^(33.0655-4330.98/Tf-9.2635*LGT(Tf)+2.0539E-3*Tf)
3175     P=P*101325/14.696
3178  END IF
3181  IF Ift=2 THEN
3184     A=9.394685-3066.1/(Tc+273.15)
3187     P=133.32*10^A
3190  END IF
3193  RETURN P
3196  FNEND
3199  DEF FNHfg(T)
3202  COM /Fld/ Ift,Istu
3205  IF Ift=0 THEN
```

```
3208      Hfg=2477200-2450*(T-10)
3211   END IF
3214   IF Ift=1 THEN
3217      Tf=T*1.8+32
3220      Hfg=7.0557857E+1-Tf*(4.838052E-2+1.2619048E-4*Tf)
3223      Hfg=Hfg*2326
3226   END IF
3229   IF Ift=2 THEN
3232      Tk=T+273.15
3235      Hfg=1.35264E+6-Tk*(6.38263E+2+Tk*.747462)
3238   END IF
3241   RETURN Hfg
3244   FNEND
3247   DEF FNMuw(T)
3250   COM /Fld/ Ift,Istu
3253   IF Ift=0 THEN
3256      A=247.8/(T+133.15)
3259      Mu=2.4E-5*10^A
3262   END IF
3265   IF Ift=1 THEN
3268      Mu=8.9629819E-4-T*(1.1094609E-5-T*5.566829E-8)
3271   END IF
3274   IF Ift=2 THEN
3277      Tk=1/(T+273.15)
3280      Mu=EXP(-11.0179+Tk*(1.744E+3-Tk*(2.80335E+5-Tk*1.12661E+8)))
3283   END IF
3286   RETURN Mu
3289   FNEND
3292   DEF FNVvst(Tt)
3295   COM /Fld/ Ift,Istu
3298   IF Ift=0 THEN
3301      P=FNPvst(Tt)
3304      T=Tt+273.15
3307      X=1500/T
3310      F1=1/(1+T*1.E-4)
3313      F2=(1-EXP(-X))^2.5*EXP(X)/X^.5
3316      B=.0015*F1-.000942*F2-.0004882*X
3319      K=2*P/(461.52*T)
3322      V=(1+(1+2*B*K)^.5)/K
3325   END IF
3328   IF Ift=1 THEN
3331      Tf=Tt*1.8+32
3334      V=13.955357-Tf*(.16127262-Tf*5.1726190E-4)
3337      V=V/16.018
3340   END IF
3343   IF Ift=2 THEN
3346      Tk=Tt+273.15
3349      P=FNPvst(Tt)
```

```
3352      V=133.95*Tk/P
3355   END IF
3358   RETURN V
3361   FNEND
3364   DEF FNCpw(T)
3367   COM /Fld/ Ift,Istu
3370   IF Ift=0 THEN
3373      Cpw=4.21120858-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7*T))
3376   END IF
3379   IF Ift=1 THEN
3382      Cpw=9.2507273E-1+T*(9.3400433E-4+1.7207792E-6*T)
3385   END IF
3388   IF Ift=2 THEN
3391      Tk=T+273.15
3394      Cpw=4.1868*(1.6884E-2+Tk*(3.35083E-3-Tk*(7.224E-6-Tk*7.61748E-9)))
3397   END IF
3400   RETURN Cpw*1000
3403   FNEND
3406   DEF FNRhow(T)
3409   COM /Fld/ Ift,Istu
3412   IF Ift=0 THEN
3415      Ro=999.52946+T*(.01269-T*(5.482513E-3-T*1.234147E-5))
3418   END IF
3421   IF Ift=1 THEN
3424      Ro=1.6207479E+3-T*(2.2186346+T*2.3578291E-3)
3427   END IF
3430   IF Ift=2 THEN
3433      Tk=T+273.15-338.15
3436      Vf=9.24848E-4+Tk*(6.2796E-7+Tk*(9.2444E-10+Tk*3.057E-12))
3439      Ro=1/Vf
3442   END IF
3445   RETURN Ro
3448   FNEND
3451   DEF FNPrw(T)
3454   Prw=FNCpw(T)*FNMuw(T)/FNKw(T)
3457   RETURN Prw
3460   FNEND
3463   DEF FNKw(T)
3466   COM /Fld/ Ift,Istu
3469   IF Ift=0 THEN
3472      X=(T+273.15)/273.15
3475      Kw=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
3478   END IF
3481   IF Ift=1 THEN
3484      Kw=8.2095238E-2-T*(2.2214286E-4+T*2.3809524E-8)
3487   END IF
```

```
3490  IF Ift=2 THEN
3493     Tk=T+273.15
3496     Kw=4.1868E-4*(519.442+.320920*Tk)
3499  END IF
3502  RETURN Kw
3505  FNEND
3508  DEF FNTanh(X)
3511  P=EXP(X)
3514  Q=EXP(-X)
3517  Tanh=(P-Q)/(P+Q)
3520  RETURN Tanh
3523  FNEND
3526  DEF FNTvsv(V)
3529  COM /Cc/ C(7)
3532  T=C(0)
3535  FOR I=1 TO 7
3538     T=T+C(I)*V^I
3541  NEXT I
3544! T=T+4.73386E-3+T*(7.692834E-3-T*8.077927E-5)
3547  RETURN T
3550  FNEND
3553  DEF FNHf(T)
3556  COM /Fld/ Ift,Istu
3559  IF Ift=0 THEN
3562     Hf=T*(4.203849-T*(5.88132E-4-T*4.55160317E-6))
3565  END IF
3568  IF Ift=1 THEN
3571     Tf=T*1.8+32
3574     Hf=8.2078571+Tf*(.19467857+Tf*1.3214286E-4)
3577     Hf=Hf*2.326
3580  END IF
3583  IF Ift=2 THEN
3586     Hf=250   ! TO BE VERIFIED
3589  END IF
3592  RETURN Hf*1000
3595  FNEND
3598  DEF FNGrad(T)
3601  Grad=37.9853+.104388*T
3604  RETURN Grad
3607  FNEND
3610  DEF FNTvsp(P)
3613  Tu=190
3616  Tl=10
3619  Ta=(Tu+Tl)*.5
3622  Pc=FNPvst(Ta)
3625  IF ABS((P-Pc)/P)>.0001 THEN
3628     IF Pc<P THEN Tl=Ta
3631     IF Pc>P THEN Tu=Ta
```

```
3634      GOTO 3619
3637  END IF
3640  RETURN Ta
3643  FNEND
6646  DEF FNSigma(T)
6649  X=647.3-T-273.15
6652  S=.1160936807/(1+.83*X)+1.121404688E-3-5.75280518E-6*X+1.28627465E-8*X^2-1
.14971929E-11*X^3
6655  RETURN S*.001*X^2
6658  FNEND
6661  SUB Raw
6662  COM /Fld/ Ift,Istu
6664  DIM X(28)
6670  INPUT "ENTER TUBE NUMBER",Itn
6676  INPUT "ENTER FILE NAME",File$
6679  ASSIGN @File TO File$
6680  INPUT "STUDENT (0=Swensen)",Istu
6681  INPUT "SMOOTH OR FINNED (0=SMOOTH, 1=FINNED)",Ifg
6683  INPUT "ENTER TUBE SIZE (0=S,1=M,2=L,3=QMC)",Itds
6685  INPUT "ENTER PRESSURE CONDITION (0=V,1=A)",Ipc
6688  IF Ipc=0 AND Ift=0 THEN Vs=2
6691  IF Ipc=0 AND Ift=2 THEN Vs=10
6692  IF Ipc=1 AND Ift=0 THEN Vs=1
6693  IF Ipc=1 AND Ift=1 THEN Vs=.25
6694  IF Istu=1 THEN Vs=2
6696  Nrun=18
6700  INPUT "ENTER NUMBER OF RUNS",Nrun
6703  PRINTER IS 701
6706  PRINT
6709  PRINT
6710  IF Istu=0 THEN PRINT USING "10X,""Data of Swensen"""
6715  IF Ift=0 THEN PRINT USING "10X,""Vapor is steam"""
6716  IF Ift=1 THEN PRINT USING "10X,""Vapor is R-113"""
6717  IF Ift=2 THEN PRINT USING "10X,""Vapor is ethylene glycol"""
6719  IF Itds=0 THEN PRINT USING "10X,""Tube diameter:   Small"""
6720  IF Itds=1 THEN PRINT USING "10X,""Tube diameter:   Medium"""
6721  IF Itds=2 THEN PRINT USING "10X,""Tube diameter:   Large"""
6722  IF Itds=3 THEN PRINT USING "10X,""Tube diameter:   QMC"""
6724  PRINT
6725  PRINT USING "10X,""Tube Number:          "",ZZ";Itn
6726  PRINT USING "10X,""File Name:            "",14A";File$
6727  IF Ifg=0 THEN PRINT USING "10X,""Tube Type:   Smooth"""
6728  IF Ifg=1 THEN PRINT USING "10X,""Tube Type:   Finned"""
6730  IF Ipc=0 THEN
6731      PRINT USING "10X,""Pressure Condition: Vacuum"""
6732  ELSE
6733      PRINT USING "10X,""Pressure Condition: Atmospheric"""
6734  END IF
```

```
6735! PRINT USING "10X,""Vapor Velocity:      "",DD.DD,"" (m/s)""";Vs
6736  ENTER @File;Ifg,Inn
6739  IF Itds=1 OR Itds=2 THEN Di=.0127
6742  IF Itds=0 OR Itds=3 THEN Di=.009525
6747  ENTER @File;Iwt,Fp,Fw,Fh
6748! IF Istu=0 AND Ifg=1 THEN
6749  IF Inam=7 THEN
6751     Fp=Fp-1
6752     PRINT USING "10X,""Fin spacing, width and height (mm): "",DD.DD,2X,Z.DD
,2X,Z.DD";Fp,Fw,Fh
6753  END IF
6756  PRINT
6757  PRINT USING "10X,""Data     Vw      Tin     Tout       Ts"""
6758  PRINT USING "10X,"" #    (m/s)     (C)      (C)      (C)"""
6760  PRINT
6763  FOR I=1 TO Nrun
6766     ENTER @File;X(*)
6769     Ts=FNTvsv57((X(8)+X(9))/2.)
6770     Ts=Ts-273.15
6772     Fm=X(3)
6775     T1=X(4)
6778     T2=X(5)
6781     Tavg=(T1+T2)*.5
6784     Ift=0
6785     Rhow=FNRhow(Tavg)
6787     Md=(6.7409*Fm+13.027)/1000.
6790     Md=Md*(1.0365-1.96644E-3*T1+5.252E-6*T1^2)/1.0037
6793     Mf=Md/Rhow
6796     Vw=Mf/(PI*Di^2/4)
6799     IF Inn=0 AND Vw>.5 THEN T2=T2-(-2.73E-4+1.75E-4*Vw+9.35E-4*Vw^2-1.96E-5
*Vw^3)
6809     IF Inn=1 THEN T2=T2-(-6.44E-5+1.71E-3*Vw+4.45E-4*Vw^2+4.07E-5*Vw^3)
6810     IF Inn=2 THEN T2=T2-(-3.99E-4+2.75E-3*Vw+1.45E-3*Vw^2+8.16E-5*Vw^3)
6811     IF Inn=3 THEN T2=T2-(8.57E-5+1.23E-3*Vw+1.08E-3*Vw^2+8.16E-5*Vw^3)
6814     PRINT USING "10X,DD,5X,D.DD,3X,2(DD.DD,3X),DDD.DD";I,Vw,T1,T2,Ts
6817  NEXT I
6820  ASSIGN @File TO *
6823  SUBEND
6826  SUB Wilson(Ci)
6829  COM /Wil/ Nrun,Itm,Iwth,Imc,Ife,Ijob,Iwd,Ifg,Ipco,Ifto,Iwil,Ihi,Ioc,Inam,K
cu,Rexp,Rm,Ax
6832  COM /Fld/ Ift,Istu
6833  COM /Geom/ D1,D2,Di,Do,L,L1,L2
6834  COM /Fric/ Istuo,Inn,Ityp,Vw,Inamo,Imco,Itds
6836  DIM Emf(20),Bvo(42),Bam(42),Eata(42),Ear(42,7),Fma(42),T1a(42),T2a(42)
6845  IF Ioc=0 THEN
6847     PRINT USING "16X,""Nusselt theory is used for Ho"""
6848  ELSE
```

```
6849      PRINT USING "16X,""Fujii correlation used for Ho"""
6850   END IF
6853   BEEP
6856   INPUT "RE-ENTER DATA FILE BEING PROCESSED",D_file$
6859   BEEP
6862   INPUT "GIVE A NAME FOR XY PLOT-DATA FILE",Plot$
6865   CREATE BDAT Plot$,30
6868   ASSIGN @Io_path TO Plot$
6871   Jj=0
6874   ASSIGN @File TO D_file$
6877   ENTER @File;Ifg,Inn
6878   IF Istu=0 THEN
6883      ENTER @File;Ddd,Ddd,Ddd,Ddd
6884   ELSE
6885      IF Ifg=0 THEN ENTER @File;Iwt
6886      IF Ifg=1 THEN ENTER @File;Fp,Fw,Fh
6887   END IF
6888   IF Istu=1 AND Inn=1 THEN Inn=2
6890   IF Jj=0 THEN
6895      IF Ihi=0 AND Inn=0 THEN Ci=.027
6896      IF Ihi=0 AND Inn=2 THEN Ci=.05
6897      IF Ihi=0 AND Inn=3 THEN Ci=.07
6899      IF Ihi=1 OR Ihi=2 THEN
6900      IF Inn=0 THEN Ci=1.0
6902      IF Inn=2 THEN Ci=2.0
6903      IF Inn=3 THEN Ci=2.5
6904      END IF
6906      IF Ifg=0 THEN Alp=1.2
6907      IF Ifg=1 THEN Alp=2.6
6908      IF Ift=2 AND Ifg=1 THEN Alp=5.0
6909   END IF
6910   J=0
6911   Sx=0
6913   Sy=0
6916   Sxs=0
6919   Sxy=0
6922! READ DATA FROM A USER-SPECIFIED FILE IF INPUT MODE (Im) = 2
6925   IF Jj=0 THEN
6926      IF Istu=0 THEN
6931         ENTER @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
6932      ELSE
6934         ENTER @File;Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),F
m,T1,T2,Phg,Pwater
6936      END IF
6938      Bvo(J)=Bvol
6939      Bam(J)=Bamp
6940      Eata(J)=Etp
6943      Ear(J,0)=Emf(0)
```

```
6946      Ear(J,1)=Emf(1)
6949      Ear(J,2)=Emf(2)
6952      Ear(J,3)=Emf(3)
6955      Ear(J,4)=Emf(4)
6956      IF Istu=1 THEN GOTO 6961
6958      Ear(J,5)=Emf(5)
6959      Ear(J,6)=Emf(6)
6960      Ear(J,7)=Emf(7)
6961      Fma(J)=Fm
6962      T1a(J)=T1
6964      T2a(J)=T2
6967   ELSE
6970      Bvol=Bvo(J)
6973      Bamm=Bam(J)
6976      Etp=Eata(J)
6979      Emf(0)=Ear(J,0)
6982      Emf(1)=Ear(J,1)
6985      Emf(2)=Ear(J,2)
6988      Emf(3)=Ear(J,3)
6991      Emf(4)=Ear(J,4)
6992      IF Istu=1 THEN GOTO 6997
6994      Emf(5)=Ear(J,5)
6995      Emf(6)=Ear(J,6)
6996      Emf(7)=Ear(J,7)
6997      Fm=Fma(J)
6998      T1=T1a(J)
7000      T2=T2a(J)
7003   END IF
7004   IF Istu=0 THEN
7006      Tsteam1=FNTvsv57(Emf(0))
7007      Tsteam1=Tsteam1-273.15
7008      Tsteam2=FNTvsv57(Emf(1))
7009      Tsteam2=Tsteam2-273.15
7010      Tsteam=Tsteam1
7011      Troom=FNTvsv58(Emf(2))
7012      Troom=Troom-273.15
7013      Tcon=FNTvsv58(Emf(7))
7014      Tcon=Tcon-273.15
7016      Ti1=FNTvsv58(Emf(3))
7017      To1=FNTvsv58(Emf(4))
7018      Ti1=Ti1-273.15
7019      To1=To1-273.15
7020      Tdel1=To1-Ti1
7021      Tdel2=T2-T1
7023      Etp1=Emf(3)+Etp/20.
7024      Dtde=2.5931E-2-1.50464E-6*Etp1+1.21701E-10*Etp1^2-5.1164E-15*Etp1^3+3.2
201E-19*Etp1^4
7025      Tris=Dtde*Etp/10.
```

```
7026     To3=Ti1+Tris
7028  ELSE
7029     Tsteam=FNTvsv(Emf(0))
7030     Ti1=FNTvsv(Emf(2))
7031     Grad=FNGrad((T1+T2)*.5)
7032     To1=Ti1+ABS(Etp)/(10*Grad)*1.E+6
7033  END IF
7034! CALCULATE THE LOG-MEAN-TEMPERATURE DIFFERENCE
7035  IF Istu=0 AND Itm=0 THEN
7036     Tcin=Ti1
7037     Tcout=To1
7038  END IF
7039  IF Itm=1 THEN
7040     Tcin=T1
7041     Tcout=T2
7042  END IF
7043  IF Itm=2 THEN
7044     Tcin=Ti1
7045     Tcout=To3
7046  END IF
7047  Tavg=(Tcin+Tcout)*.5
7048  Trise=Tcout-Tcin
7049! PRINT Trise
7055  Ift=0
7056  Cpw=FNCpw(Tavg)
7057  Rhow=FNRhow(Tavg)
7058  Kw=FNKw(Tavg)
7059  Muwa=FNMuw(Tavg)
7060  Prw=FNPrw(Tavg)
7061  Ift=Ifto
7062  IF Istu=0 THEN
7063     Mdt=(6.7409*Fm+13.027)/1000.
7064     Md=Mdt*(1.0365-Tcin*(1.96644E-3-Tcin*5.252E-6))/1.0037
7065  ELSE
7066     Mdt=1.04805E-2+6.80932E-3*Fm
7067     Md=Mdt*(1.0365-Tcin*(1.96644E-3-Tcin*5.252E-6))/.995434
7068  END IF
7069  Vf=Md/Rhow
7070  Vw=Vf/(PI*Di^2/4)
7071  Tcor=FNTfric(Trise)
7072  Trise=Tcor
7073  Tcout=Tcin+Trise
7074  Lmtd=Trise/LOG((Tsteam-Tcin)/(Tsteam-Tcout))
7077  Cpsc=FNCpw((Tcon+Tsteam)*.5)
7078  Hfg=FNHfg(Tsteam)
7079  Ql=500
7080  Qloss=Ql/(100-25)*(Tsteam-Troom)  ! TO BE MODIFIED
7082  Mdv=0
```

```
7084  Bp=(Bvol*100)^2/5.76
7085  Hsc=Cpsc*(Tsteam-Tcon)
7086  Mdvc=((Bp-Qloss)-Mdv*Hsc)/Hfg
7088  IF ABS((Mdv-Mdvc)/Mdvc)>.01 THEN
7090     Mdv=(Mdv+Mdvc)*.5
7092     GOTO 7086
7094  END IF
7096  Mdv=(Mdv+Mdvc)*.5
7098  Vg=FNVvst(Tsteam)
7100  Vv=Mdv*Vg/Ax
7108  Q=Md*Cpw*Trise
7111  Qp=Q/(PI*Do*L)
7114  Uo=Qp/Lmtd
7115! PRINT Trise,Vw,Q,Do,L,Qp,Lmtd,Uo
7117  Rei=Rhow*Vw*Di/Muwa
7120  Fe1=0.
7123  Fe2=0.
7126  Cf=1.
7127  Prwf=Prw
7128  Reif=Rei
7131  Two=Tsteam-5
7132  Tfilm=Tsteam/3+Two*2/3
7135  Kf=FNKw(Tfilm)
7138  Rhof=FNRhow(Tfilm)
7141  Muf=FNMuw(Tfilm)
7144  Hfgp=FNHfg(Tsteam)+.68*FNCpw(Tfilm)*(Tsteam-Two)
7145  IF Ioc=0 THEN
7147! New=Kf*(Rhof^2*9.81*Hfgp/(Muf*Do*Qp))^.3333
7148  New=(Kf^3*9.81*Hfgp*Rhof^2/(Muf*Do*(Tsteam-Two)))^.25
7150  ELSE
7153! New=Kf*((9.81*Hfgp/Qp)^.25)*((Muf*Do)^(-.375))*(Rhof^.625)*(Vv^.125)
7154  New=(9.81*Hfgp/(Tsteam-Two))^.2*Kf^.8*Vv^.1*Rhof^.5/(Do*Muf)^.3
7156  END IF
7159  Ho=Alp*New
7162  Twoc=Tsteam-Qp/Ho
7165  IF ABS((Twoc-Two)/Twoc)>.001 THEN
7168     Two=Twoc
7171     GOTO 7132
7174  END IF
7184  IF Ihi=0 THEN
7186     Omega=Rei^Rexp*Prw^.3333*Cf
7187  END IF
7188  IF Ihi=1 THEN
7189     Sra=.88-(.24/(4.+Prwf))
7190     Srb=.333333+.5*EXP(-.6*Prwf)
7191     Omega=(5.+.015*Reif^Sra*Prwf^Srb)
7192  END IF
7193  IF Ihi=2 THEN
```

```
7194      Epsi=(1.82*LGT(Rei)-1.64)^(-2)
7195      Ppk1=1.+3.4*Epsi
7196      Ppk2=11.7+1.8*Prw^(-1/3)
7197      Pp1=(Epsi/8)*Rei*Prw
7198      Pp2=(Ppk1+Ppk2*(Epsi/8)^.5*(Prw^.6666-1))
7199      Omega=Pp1/Pp2
7200   END IF
7202   Hi=Kw/Di*Ci*Omega
7203   IF Ife=0 THEN 7216
7204   P1=PI*(Di+D1)
7205   P2=PI*(Di+D2)
7206   A1=(D1-Di)*PI*(Di+D1)*.5
7207   A2=(D2-Di)*PI*(Di+D2)*.5
7208   M1=(Hi*P1/(Kcu*A1))^.5
7209   M2=(Hi*P2/(Kcu*A2))^.5
7212   Fe1=FNTanh(M1*L1)/(M1*L1)
7213   Fe2=FNTanh(M2*L2)/(M2*L2)
7216   Dt=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
7217   IF Ihi=0 THEN
7219      Muwi=FNMuw(Tavg+Dt)
7222      Cfc=(Muwa/Muwi)^.14
7225      IF ABS((Cfc-Cf)/Cfc)>.001 THEN
7228         Cf=(Cf+Cfc)*.5
7231         GOTO 7184
7232      END IF
7234   END IF
7235   IF Ihi=1 THEN
7236      Prwfc=FNPrw(Tavg+Dt)
7237      Reifc=Vw*Di*FNRhow(Tavg+Dt)/FNMuw(Tavg+Dt)
7239      IF ABS((Prwfc-Prwf)/Prwfc)>.001 OR ABS((Reifc-Reif)/Reifc)>.001 THEN
7240         Prwf=(Prwfc+Prwf)/2.
7241         Reif=(Reifc+Reif)/2.
7242         GOTO 7184
7243      END IF
7245   END IF
7246   Ift=Ifto
7247   X=Do*New*L/(Omega*Kw*(L+L1*Fe1+L2*Fe2))
7248   Y=New*(1/Uo-Rm)
7249! COMPUTE COEFFICIENTS FOR THE LEAST-SQUARES-FIT STRAIGHT LINE
7250   IF Jp=1 THEN OUTPUT @Io_path;X,Y
7252   Sx=Sx+X
7255   Sy=Sy+Y
7258   Sxs=Sxs+X*X
7261   Sxy=Sxy+X*Y
7264   IF Im=1 AND Jj=0 THEN OUTPUT @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(
*)
7267   J=J+1
7270   IF J<Nrun THEN 6925
```

```
7273  Sl=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxs-Sx^2)
7276  IF Iwil=2 THEN
7286     IF Ihi=0 AND Inn=0 THEN Sl=1/.027
7287     IF Ihi=0 AND Inn=2 THEN Sl=1/.05
7288     IF Ihi=0 AND Inn=3 THEN Sl=1/.07
7289     IF Ihi=1 OR Ihi=2 THEN
7291     IF Inn=0 THEN Sl=1/1.0
7292     IF Inn=2 THEN Sl=1/2.0
7293     IF Inn=3 THEN Sl=1/2.5
7294     END IF
7296  END IF
7297  Ac=(Sy-Sl*Sx)/Nrun
7298  Cic=1/Sl
7300  Alpc=1/Ac
7303  Jj=Jj+1
7306  IF Jp=1 THEN Jp=2
7309  Cerr=ABS((Cic-Ci)/Cic)
7312  Aerr=ABS((Alpc-Alp)/Alpc)
7315  IF Cerr>.001 OR Aerr>.001 THEN
7318     Ci=(Cic+Ci)*.5
7321     Alp=(Alpc+Alp)*.5
7324     BEEP
7327     IF Ijob=1 THEN 6910
7330  ELSE
7333     IF Jp=0 THEN Jp=1
7336  END IF
7339  IF Jp=1 THEN 6874
7342  Ci=(Ci+Cic)*.5
7345  PRINT
7346  IF Ihi=0 THEN
7348     PRINT USING "10X,""Ci (based on Sieder-Tate)       =  "",Z.4D";Ci
7349  END IF
7350  IF Ihi=1 THEN
7351     PRINT USING "10X,""Ci (based on Sleicher-Rouse)    =  "",Z.4D";Ci
7352!    PRINT USING "10X,""Re exponent for Sleicher-Rouse  =  "",D.DDD";Sra
7353  END IF
7354  IF Ihi=2 THEN
7355     PRINT USING "10X,""Ci (based on Petukhov-Popov)    =  "",Z.4D";Ci
7356  END IF
7357  IF Ioc=0 THEN
7358     PRINT USING "10X,""Alpha (based on Nusselt (Tdel)) =  "",Z.4D";Alp
7359  END IF
7360  IF Ioc=1 THEN
7361     PRINT USING "10X,""Alpha (based on Fujii (Tdel))   =  "",Z.4D";Alp
7362  END IF
7363  IF Inam=5 OR Inam=6 THEN
7364     IF Ihi=0 THEN
7366        IF Ipco=0 AND Inn=0 THEN Alpsm=.8218  !NO INSERT,VACUUM,S-T
```

```
7367        IF Ipco=1 AND Inn=0 THEN Alpsm=.7793  !NO INSERT,ATMOSPHERIC,S-T
7368        IF Ipco=0 AND Inn=3 THEN Alpsm=.7854  !HEATEX,VACUUM,S-T
7369        IF Ipco=1 AND Inn=3 THEN Alpsm=.7769  !HEATEX,ATMOSPHERIC,S-T
7371     END IF
7372     IF Ihi=1 THEN
7373        IF Ipco=0 AND Inn=0 THEN Alpsm=.8613  !NO INSERT,VACUUM,S-R
7374        IF Ipco=1 AND Inn=0 THEN Alpsm=.8218  !NO INSERT,ATMOSPHERIC,S-R
7375        IF Ipco=0 AND Inn=3 THEN Alpsm=.7791  !HEATEX,VACUUM,S-R
7376        IF Ipco=1 AND Inn=3 THEN Alpsm=.7929  !HEATEX,ATMOSPHERIC,S-R
7378     END IF
7379     IF Ihi=2 THEN
7380        IF Ipco=0 AND Inn=0 THEN Alpsm=.8205  !NO INSERT,VACUUM,P-P
7381        IF Ipco=1 AND Inn=0 THEN Alpsm=.7654  !NO INSERT,ATMOSPHERIC,P-P
7382        IF Ipco=0 AND Inn=3 THEN Alpsm=.7670  !HEATEX,VACUUM,P-P
7383        IF Ipco=1 AND Inn=3 THEN Alpsm=.7708  !HEATEX,ATMOSPHERIC,P-P
7385     END IF
7386  END IF
7387  IF Inam=4 THEN
7390     IF Ipco=1 THEN Alpsm=.876  !SWENSEN DATA BASED ON DEL-T
7391  END IF
7392  IF Inam=0 OR Inam=3 OR Inam=7 THEN
7393     IF Ipco=0 THEN Alpsm=.81   !COBB VTSMTH1
7394     IF Ipco=1 THEN Alpsm=.85   !COBB ATSMTH1
7396     IF Ift=1 THEN Alpsm=.733   !ZEBROWSKI (V = 0.45 m/s)
7397     IF Ift=1 THEN Alpsm=.677   !VAN PETTEN (V = 0.25 m/s)
7398     IF Ift=2 THEN Alpsm=1.262
7399  END IF
7401  IF Inam=1 THEN  !MITROU ALPHA FOR P-P FROM REPROCESSING
7402     IF Ipco=0 THEN Alpsm=.8437
7403     IF Ipco=1 THEN Alpsm=.8418
7404  END IF
7405  Et=Alp/Alpsm
7406  Eq=Et^1.333333
7407  PRINT USING "10X,""Enhancement (q)                  = "",DD.3D";Eq
7408  PRINT USING "10X,""Enhancement (Del-T)              = "",DD.3D";Et
7409  ASSIGN @File TO *
7410  SUBEND
7519  SUB Modify
7520  COM /Fld/ Ift,Istu
7522  DIM Emf(20)
7525  BEEP
7528  INPUT "ENTER NAME OF FILE TO BE MODIFIED",Fileo$
7531  ASSIGN @Fileo TO Fileo$
7534  CREATE BDAT "TEST",30
7537  ASSIGN @Filed TO "TEST"
7540  ENTER @Fileo;Ifg,Inn
7543  OUTPUT @Filed;Ifg,Inn
```

```
7544  IF Istu=0 THEN
7546     ENTER @Fileo;Iwt,Fp,Fw,Fh
7547     OUTPUT @Filed;Iwt,Fp,Fw,Fh
7548  ELSE
7549     IF Ifg=0 THEN
7551        ENTER @Fileo;Iwt
7552        OUTPUT @Filed;Iwt
7553     END IF
7554     IF Ifg=1 THEN
7555        ENTER @Fileo;Fp,Fw,Fh
7556        OUTPUT @Filed;Fp,Fw,Fh
7557     END IF
7559  END IF
7560  BEEP
7561  INPUT "ENTER NUMBER OF DATA SETS STORED",N
7562  FOR I=1 TO N
7563     IF Istu=0 THEN
7565        ENTER @Fileo;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
7566     ELSE
7567        ENTER @Fileo;Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),
Fm,T1,T2,Phg,Pwater
7568     END IF
7570!   PERFORM CORRECTIONS
7571     PRINT USING "2X,""DO YOU WISH TO DELETE POINT"",DD,""?""";I
7572     INPUT "0=YES, 1=NO",Idel
7573     IF Idel=0 THEN 7580
7576     IF Istu=0 THEN
7577        OUTPUT @Filed;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
7578     ELSE
7579        OUTPUT @Filed;Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4)
,Fm,T1,T2,Phg,Pwater
7580     END IF
7581  NEXT I
7582  ASSIGN @Fileo TO *
7583  ASSIGN @Filed TO *
7584  SUBEND
7585  SUB Purg
7588  BEEP
7591  INPUT "ENTER FILE NAME TO BE DELETED",File$
7594  PURGE File$
7597  GOTO 7588
7600  SUBEND
7690  SUB Renam
7693  BEEP
7696  INPUT "ENTER FILE NAME TO BE RENAMED",File1$
7699  BEEP
7702  INPUT "ENTER NEW NAME FOR FILE",File2$
7705  RENAME File1$ TO File2$
```

```
7708  GOTO 7693
7711  SUBEND
7721  DEF FNTvsv55(V)
7731  COM /Cc55/ T55(5)
7741  T=T55(0)
7751  FOR I=1 TO 5
7761     T=T+T55(I)*V^I
7771     NEXT I
7781  RETURN T
7791  FNEND
7801  DEF FNTvsv56(V)
7811  COM /Cc56/ T56(5)
7821  T=T56(0)
7831  FOR I=1 TO 5
7841     T=T+T56(I)*V^I
7851  NEXT I
7861  RETURN T
7871  FNEND
7881  DEF FNTvsv57(V)
7891  COM /Cc57/ T57(5)
7901  T=T57(0)
7911  FOR I=1 TO 5
7921     T=T+T57(I)*V^I
7931  NEXT I
7941  RETURN T
7951  FNEND
7961  DEF FNTvsv58(V)
7971  COM /Cc58/ T58(5)
7981  T=T58(0)
7991  FOR I=1 TO 5
8001     T=T+T58(I)*V^I
8011  NEXT I
8021  RETURN T
8031  FNEND
8100  DEF FNTfric(Tcor)
8110  COM /Fric/ Istuo,Inn,Ityp,Vw,Inamo,Imco,Itds
8113  IF Itds=3 AND Inn=3 THEN  ! COBB'S TUBES (Di=12.7mm)
8114     Tcor=Tcor-(2.524E-5-1.6958E-3*Vw+7.1064E-3*Vw^2-3.318E-3*Vw^3+8.5545E-4
*Vw^4-7.37E-5*Vw^5)
8115     GOTO 8300
8116  END IF
8121  IF (Itds=1 OR Itds=2) AND Imco=0 THEN ! MEDIUM AND LARGE COPPER TUBES (Di=
12.7mm)
8122     IF Inn=0 AND Vw>.5 THEN Tcor=Tcor-(-2.73E-4+1.75E-4*Vw+9.35E-4*Vw^2-1.9
6E-5*Vw^3)
8130     IF Inn=1 THEN Tcor=Tcor-(-6.44E-5+1.71E-3*Vw+4.45E-4*Vw^2+4.07E-5*Vw^3)
8140     IF Inn=2 THEN Tcor=Tcor-(-3.99E-4+2.75E-3*Vw+1.45E-3*Vw^2+8.16E-5*Vw^3)
8150     IF Inn=3 THEN Tcor=Tcor-(8.57E-5+1.23E-3*Vw+1.08E-3*Vw^2+8.16E-5*Vw^3)
```

```
8151     GOTO 8300
8160  END IF
8170  IF (Ityp=0 OR Ityp=2) AND Imco=4 THEN ! SMOOTH AND WIRE-WRAPPED TITANIUM T
UBE (Di=13.86mm)
8180     IF Inn=0 AND Vw>.5 THEN Tcor=Tcor-(-4.62E-5-7.53E-4*Vw+1.80E-3*Vw^2-8.8
4E-5*Vw^3)
8190     IF Inn=3 AND Inamo=5 THEN Tcor=Tcor-(2.09E-4+9.74E-4*Vw+2.12E-3*Vw^2-3.
31E-5*Vw^3)
8191     IF Inn=3 AND Inamo=6 THEN Tcor=Tcor-(1.9555E-4+3.9721E-3*Vw+3.127E-4*Vw
^2+3.519E-4*Vw^3)
8192     GOTO 8300
8201  END IF
8210  IF (Ityp=3 OR Ityp=4) AND Itds=4 THEN ! LPD KORODENSE (Di=13.47mm)
8220     IF Inn=0 AND Vw>.5 THEN Tcor=Tcor-(-3.386E-4+1.88E-3*Vw+6.013E-4*Vw^2+4
.133E-5*Vw^3)
8230     IF Inn=3 THEN Tcor=Tcor-(2.089E-4+9.202E-4*Vw+1.893E-3*Vw^2-2.781E-5*Vw
^3)
8231     GOTO 8300
8240  END IF
8242  IF (Ityp=5 OR Ityp=6) AND Itds=4 THEN ! MHT KORODENSE (Di=13.53mm)
8245     IF Inn=0 AND Vw>.5 THEN Tcor=Tcor-(6.79E-5+1.632E-3*Vw+8.409E-4*Vw^2+1.
111E-4*Vw^3)
8246     IF Inn=3 THEN Tcor=Tcor-(2.564E-4+6.263E-4*Vw+2.603E-3*Vw^2+7.830E-6*Vw
^3)
8247     GOTO 8300
8249  END IF
8250  IF Itds=0 AND Imco=0 THEN !SMALL COPPER TUBE (Di=9.525mm)
8260     IF Inn=0 THEN Tcor=Tcor-(.0138+.001*Vw^2)
8270     IF Inn=1 THEN Tcor=Tcor-.004*Vw^2
8280     IF Inn=2 THEN Tcor=Tcor-.004*Vw^2
8290  END IF
8300  RETURN Tcor
8310  FNEND
8500  SUB Mergefile
8510  DIM Emf(20)
8520  BEEP
8530  INPUT "ENTER NAME OF NEW FILE",D_file$
8540  CREATE BDAT D_file$,50
8550  ASSIGN @Filed TO D_file$
8560  BEEP
8570  Numb=0
8580  BEEP
8590  INPUT "NUMBER OF FILES TO MERGE",N
8600  IF Numb=N THEN 8770
8610  Numb=Numb+1
8620  BEEP
8630  INPUT "ENTER FILE TO BE MERGED",Fileo$
8640  ASSIGN @Fileo TO Fileo$
```

```
8650  ENTER @Fileo;Ifg,Inn
8660  IF Numb=1 THEN OUTPUT @Filed;Ifg,Inn
8670  ENTER @Fileo;Iwt,Fp,Fw,Fh
8680  IF Numb=1 THEN OUTPUT @Filed;Iwt,Fp,Fw,Fh
8690  BEEP
8700  INPUT "ENTER NUMBER OF DATA SETS STORED",Nrun
8710  FOR I=1 TO Nrun
8720      ENTER @Fileo;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
8730      OUTPUT @Filed;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
8740  NEXT I
8750  ASSIGN @Fileo TO *
8760  GOTO 8600
8770  ASSIGN @Filed TO *
8780  SUBEND
8790  SUB Xyoutput
8791  PRINTER IS 1
8800  INPUT "ENTER NAME OF PLOT DATA FILE",Filep$
8810  ASSIGN @Filep TO Filep$
8820  INPUT "ENTER NUMBER OF DATA POINTS",Npts
8821  PRINTER IS 701
8830  FOR I=1 TO Npts
8840     ENTER @Filep;X,Y
8850     PRINT X,Y
8860  NEXT I
8870  ASSIGN @Filep TO *
8880  SUBEND
```

APPENDIX B. TEMPERATURE RISE CORRECTION

As coolant flows through the tube there is an increase in the bulk temperature of the fluid due to frictional heating. The amount of frictional heat added to the system depends on the fluid velocity and the inside geometry of the tube. The actual measured increase in temperature is small but the increase has a significant effect on the calculated overall heat transfer coefficient and later calculations. The correctional equation below:

$$T_{cor} = 2.524e{-5} - 1.6958e{-3} * V_{cw} + 7.1064e{-3} * V_{cw}^2 - 3.318e{-3} * V_{cw}^3 + 8.5545e{-4} * V_{cw}^4 - 7.37e{-5} * V_{cw}^5 \quad \text{(B.1)}$$

where T_{cor} is the temperature rise (K) and V_{cw} is the fluid velocity (m/s). Equation (B.1) was determined by measuring the temperature difference between the inlet and outlet thermocouples for various cooling water flow rates through a test tube with a Heatex insert and no external heat source (i.e., no steam in the test system). The flow rates were converted into velocities and plotted against the temperature difference as shown in Figure B.1. Equation (B.1) was the curve fit of the obtained data. The temperature rise correctional value was subtracted from the measured temperature difference during the data runs to determine the

actual heat transferred to the cooling water conducted from the steam.

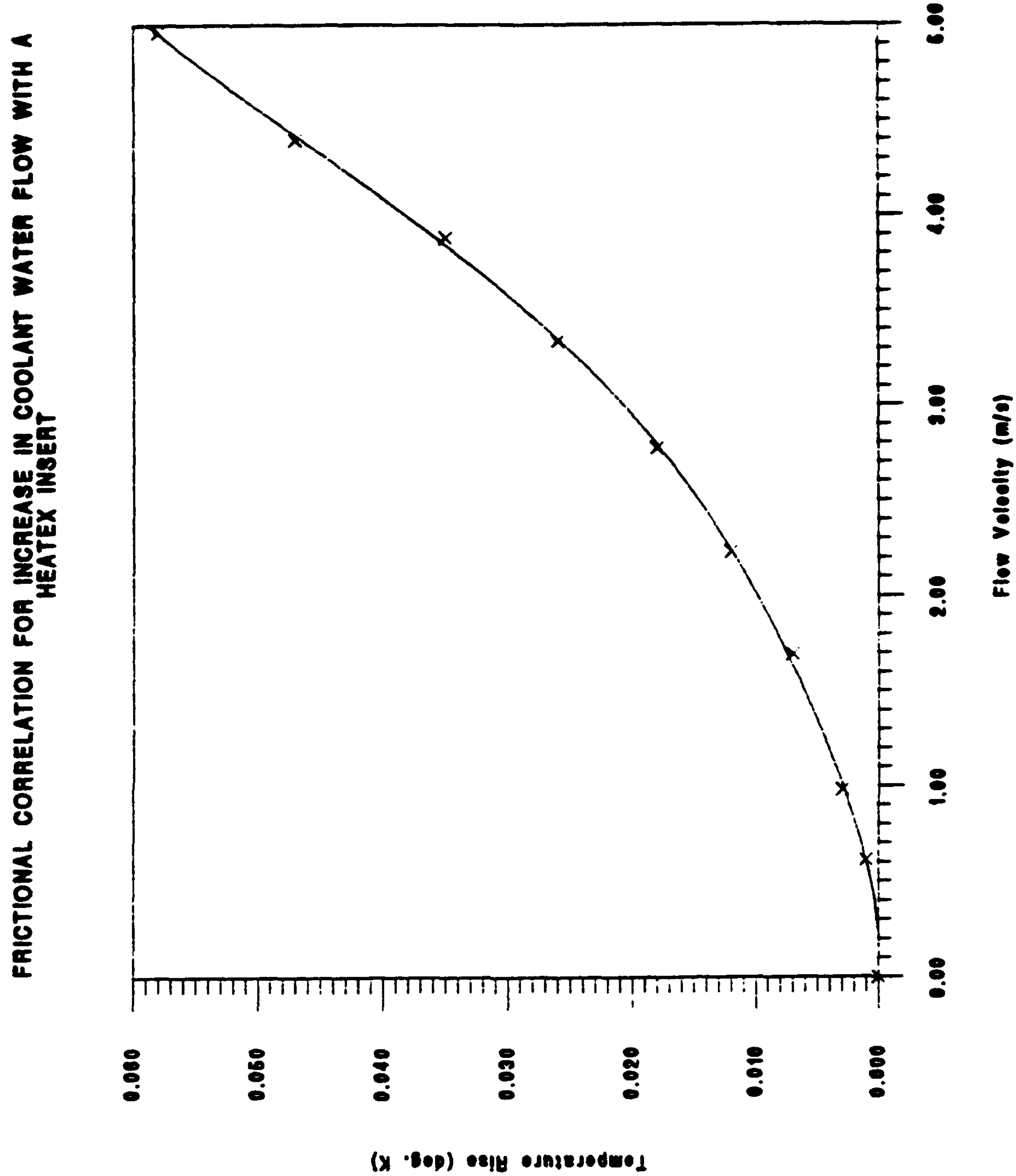

Figure B.1 Frictional Correlation for the Increase in Coolant Water Temperature due to a change in Velocity Flow and a Heatex Insert

APPENDIX C. MODEL PROGRAM LISTING

The program HEATCOBB, which was used to reprocess the temperature values obtained, from the data collection program DRPALL, to predict the outside heat transfer coefficients and enhancement ratios for a constant temperature differences (ΔT), is listed in this Appendix.

```
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 DBSI0, DBSI1, DBSK0, DBSK1,  KC,
     *      W, WC, R2C, A,G, DT(20,3),PITCH, Y,QFF(1000),
     *      R1,R2,NU,RB,D2,DR,RHOF(1000),RHOG(1000),RHO(1000),
c    *      EFF(1000), X1(1000), X2(1000),CH(1000),Z(1000),
c    *      AFS(1000), AFT(1000),AU(1000),DF(1000),
c    *      Y(1000), LA(1000), AEF(1000), DE(1000), HMF(1000),
cccccccccccccccccccccccccc
c     THE ARRAY VALUES ABOVE ARE USE FOR THE OVERALL RANGE OF FIN
c     EFFICIENCIES AND HEAT TRANSFER COEFFICIENTS. FOR A SPECIFIC
c     FIN EFFICIENCY OR HEAT TRANSFER COEFFICIENT USE THE CONSTANT/
c     SCALER VALUES BELOW. ONE MUST BE COMMENTED OUT!!!
cccccccccccccccccccccc
     *      ETA, X1,X2,AEF,LA,AFS,AFT,DE,AU,DF,CH,Z,HMF,
     *      L1,L2,AO,RATIO,THICK,SPACEB,SPACET,TOL,LEN,TSTEAM(1000),
     *    P(1000),VF(1000),HFG(1000),CPF(1000),TFILM(1000),TFC(1000),
     *   UG(1000),KF(1000),PRF(1000),SIGMA(1000),CPG(1000),UF(1000),
     *  VG(1000),BETA,BT,BF,BS,B1,PHI(1000),FF(1000),FS(1000),HV(1000),
     *  QT(1000),QF(1000),QS(1000),EPH(1000),QQF(1000),QQS(1000),
     *  QNUS(1000),GT(1000),EDT(1000),GS(1000),GF(1000),TF(1000),
     *  TS(1000),TT(1000),EDTC(1000),TSTM(20,1),TFLM(20,2),HO(20,4),
     *  HS(1000),HF(1000),HN(1000),ENH,
     *  HBKSMH,HNSMH,HNUSS,FFI(1000),FSI(1000),PHIP(1000),
     *  F1(1000),F2(1000),Arf(1000),Ar(1000),Atr(1000),Ats(1000),
     *  RSA(1000),IEAA(1000),MAXENH(1000),AT,AF(1000),AS(1000),
     *  ATOTAL(1000),HR(1000)

      PARAMETER (PI=3.141592654)


      INTEGER L,F,J,TM,AREA,JJ

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c    NU:       NUMBER OF FINS PER UNIT LENGTH
c    LEN:      CONDENSING LENGTH OF TUBE
c    L1:       LENGTH PRIOR TO CONDENSING LENGTH THAT ACTS AS A FIN
c    L2:       LENGTH AFTER THE CONDENSING LENGTH THAT ACTS AS A FIN
c    KC:       THERMAL CONDUCTIVITY OF THE TUBE MATERIAL
c    W:        ==> FIN HEIGHT (h)
c    DR:       ROOT DIAMETER OF TUBE
c    D2:       OUTER DIAMETER AT FIN TIP
c    SPACET:   SPACING AT THE TIP OF THE FIN (b)
c    SPACEB:   SPACING AT THE BASE OF THE FIN (s)
c    G:        GRAVITY FORCE
c    CH:       INPUT HEAT TRANSFER COEFF USED TO DETERMINE THE HTC WITH
c             * THE EFFICIENCY FOR THE MATERIAL
c    ETA:      FIN EFFICIENCY
c    PITCH:    FIN PITCH
c    P:        PRESSURE AT THE STEAM TEMPERATURE
c    VF:       SPECIFIC VOLUME OF THE CONDENSATE AT THE FILM TEMPERATURE
c    VG:       SPECIFIC VOLUME OF THE STEAM VAPOR
c    RHOF:     THE DENSITY OF THE CONDERSATE
c    RHOG:     THE DENSITY OF THE STEAM VAPOR
c    RHO:      THE DIFFERENCE BETWEEN THE TWO DENSITIES
c    HFG:      HEAT OF VAPORIZATION AT THE VAPOR TEMPERATURE
c    CPF:      SPECIFIC VOLUME OF CONDENSATE
c    CPG:      SPECIFIC VOLUME OF CONDENSATE
c    UF:       VISCOSITY OF CONDENSATE
c    UG:       VISCOSITY OF STEAM
```

```
C     KF:       THERMAL CONDUCTIVITY OF CONDENSATE
C     PRF:      PRANDTL NUMBER OF CONDENSATE
C     SIGMA:    SURFACE TENSION OF CONDENSATE
C     HMF:      HBK: HEAT TRANSFER COEFFICIENT BASED ON BEATTY AND KATZ
C             * CORRELATION
C     HNUSS:    HEAT TRANSFER COEFFICIENT BASED ON NUSSELT CORRELATION
C     AU:       UNFINNED SURFACE AREA
C     AFS:      AREA OF FIN FLANK
C     AFT:      AREA OF FIN TIP
C     AEF:      EFFECTIVE SURFACE AREA WITH FINS
C     DE:       EFFECTIVE DIAMETER WITH FIN
C     AO:       AURFACE AREA OF SMOOTH TUBE WITH OUTSIDE DAIMETER OF
C           *   ROOT (WITHOUT FINS)
C     L:        D: ADDITIONAL HEIGHT OF RADIUSED FIN ROOTS
C     QQF:      TOTAL HEAT TRANSFER RATE OVER ENTIRE LENGTH FOR A FIN TUBE
C     QQS:      TOTAL HEAT TRANSFER RATE OVER A SMOOTH TUBE WITH DIAMETER
C           *   EQUAL TO THE ROOT DIAMETER
C     QNUS:     TOTAL HEAT TRANSFER RATE BASED ON NUSSELT CORRELATION
C     EDT:      ENHANCEMENT RATIO (HEAT-TRANSFER COEFFICIENT FOR FINNED
C           *   TUBE DIVIDED BY THE HEAT TRANSFER COEFFICIENT FOR A SMOOTH
C           *   TUBE WITH THE SAME DIAMETER)
C     GS:       CONSTANT VALUE IN EQN
C     TS:       CONSTANT VALUE IN EQN
C     GF:       CONSTANT VALUE IN EQN
C     TF:       CONSTANT VALUE IN EQN
C     EDTC:     CHECK OT THE ENHANCEMENT RATIO
C     TT:       CONSTANT VALUE IN EQN
C     GT:       CONSTANT VALUE IN EQN
C     BT:       CONSTANT VALUE FOR b AT FIN TIP
C     BF:       CONSTANT VALUE FOR b AT FIN FLANK
C     BS:       CONSTANT VALUE FOR b FOR INTERFIN TUBE SPACING
C     B1:       CONSTANT VALUE
C     BETA:     HALF-ANGLE AT THE FIN TIP
C     PHI:      CONDENSATE RETENTION OR "FLOODING" ANGLE FROM TOP OF TUBE
C     FF:       FRACTION OF UNFLOODED PART BLANKED BY RETAINED CONDENSATE
C           *   AT FIN ROOT
C     FS:       FRACTION OF UNFLOODED PART OF INTERFIN TUBE SURFACE
C           *   BLANKED BY RETAINED CONDENSATE AT FIN ROOT
C     HV:       EFFECTIVE MEAN VERTICAL FIN HEIGHT
C     QT:       HEAT FLUX FOR FIN TIP
C     QF:       HEAT FLUX FOR FIN FLANK
C     QS:       HEAT FLUX FOR TUBE SURFACE BETWEEN FINS
C     EPH:      FUNCTION VLAUE OF CONDENSATE RETENTION ANGLE
C     THICK:    FIN THICKNESS (t)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      OPEN (15, FILE= 'HEATCOBB OUTPUT')

c     select type of material (tm)
c     0-copper, 1-stainless steel, 2-aluminum, 3-copper nickel
      TM= 2

c     select surface area equation (area)
c     1-rectangular fin, 2-deep fillet radius, 3-shallow fillet radius

      AREA= 3

c     select the number of data points

      F= 14
```

```
      IF (TM .EQ. 0) THEN
         kc= 390.82
         write(15,*) 'type material- copper'
         write(15,*) 'thermal conductivity (kc):',kc
C         END IF

      ELSEIF (TM .EQ.1) THEN
         kc= 14.3
         write(15,*) 'type material- stainless steel'
         write(15,*) 'thermal conductivity (kc):',kc
C     END IF

      ELSEIF (TM .EQ. 2) THEN
         kc= 231.8
         write(15,*) 'type material- aluminum'
         write(15,*) 'thermal conductivity (kc):',kc
C         END IF

      ELSE
         kc= 55.3
         write(15,*) 'type material- copper nickel'
         write(15,*) 'thermal conductivity (kc):',kc
      end if

      IF (AREA .EQ. 3) THEN
         dr= 14.38e-3
         W =.75E-3
      else
         W =1E-3
         dr= 13.88e-3
      end if

C     DR= 13.7E-3
      LEN= .13335
      L1= .060325
      L2= .034925
      BETA= 0
      BT=  0.143
      BF=  0.143
      BS=   0.143
      B1=  2.96
      THICK= 1*10.**(-3)
      S=1.5E-3
      JJ=0
C     DO 5 S= .5E-3,2.5E-3,.05E-3
C     SPACEB= 2.5 * 10.**(-3)
      SPACEB= S
C     JJ= JJ+1
C     WRITE (15,*) 'RUN NUMBER =',JJ
      SPACET= SPACEB
      OPEN (16, FILE= 'VT131 FORTRAN')
      WRITE(15,*) 'OUTPUT FOR VT131'


      PITCH= SPACEB+THICK
C      W = 0.000001
      R1= DR/2.
      D2= DR + 2*W
      R2= D2/2.
      WC= W + THICK/2.
```

```
      R2C= R2 + THICK/2.
      RA= SQRT(2.)/(1. - R1/R2C)
      RB= (R1/R2C) * RA
      T= THICK
      L= .25e-3

      WRITE(15,*) 'DR=',DR
      WRITE(15,*) 'FIN HEIGHT =',W
      IF (AREA .EQ.1) THEN
         A= t*wc
         WRITE(15,*) 'RECTANGULAR FIN'
         ASC= A
      end if

      IF (AREA .EQ.2) THEN
C        A= (L+T/2)*T+(T*SPACET)*SPACET/2-(PI*SPACET**2/8)
         write(15,*) 'deep fillet radius fin'
         A=(T/2+W)*(T+SPACET)-SPACET*((R2-(R1+SPACET/2))+T/2)
     *      -PI/2*(SPACET/2)**2

C        WRITE(15,*) 'SURFACE AREA:',A
         Asc= (t+spacet)*(L+spacet/2+t/2)-(((L+t/2)*spacet)+
     *        (pi*spacet**2)/8)
C        WRITE(15,*) 'SURFACE AREA (COBB):',ASC
       end if

      IF (AREA .EQ.3) THEN
C         A=(T/2+W)*(T+SPACET)-SPACET*((R2-(R1+SPACET/2))+T/2)
C    *      -PI/2*(SPACET/2)**2
C        A= (T/2)*T+(T*SPACET)*SPACET/2-(PI*SPACET**2/8)
         A=(T/2+W)*(T+SPACET)-SPACET*((R2-(R1+SPACET/2))+T/2)
     *      -PI/2*(SPACET/2)**2
         write(15,*) 'shallow fillet radius fin'
C        WRITE(15,*) 'SURFACE AREA:',A
C        ASC= (T+SPACET)*(SPACET/2+T/2)-(((T/2)*SPACET)+
C    *         (PI*SPACET**2)/8)
C        WRITE(15,*) 'SURFACE AREA (COBB):',A
       end if


C     A= THICK * WC
      WRITE(15,*) 'CROSS SECTION AREA:',A

      NU= (1/PITCH) * LEN
      G= 9.81
      DO 10 J=1,F
          READ (16,46) TSTM(J,1),TFLM(J,2),DT(J,3),HO(J,4)
 46       FORMAT (2X,F7.3,4X,F6.3,4X,F5.2,4X,F7.1)
          TSTEAM(J)= 273.15 + TSTM(J,1)

          TFC(J)= TSTEAM(J)/3. + 2*(TSTEAM(J)-DT(J,3))/3.
          TFILM(J)= TFLM(J,2) + 273.15
          WRITE(15,46) TSTM(J,1),TFLM(J,2),DT(J,3),HO(J,4)
C         WRITE(15,*) 'TFILM:',TFILM(J)
          WRITE(15,*) 'NUM INPUT:',J
C         WRITE(15,*) 'TSTEAM:',TSTEAM(J)
C         WRITE(15,*) 'TFILM CALC :', TFC(J)

        P(J)= 2.003732620063*10.**3 -1.77885208776858*10.**1
```

```
*          *TSTEAM(J) + 6.697864486474*10.**(-3)*TSTEAM(J)**2 +
*           3.86086914584487*10.**(-4)*TSTEAM(J)**3 -
*          1.404502413839*10.**(-6)*TSTEAM(J)**4 +
*          1.51673236206257*10.**(-9)*TSTEAM(J)**5

    VF(J)= 5.923643369271*10.**(-3)-6.64076036569*10.**(-5)
*         *TFILM(J) + 3.569837849015*10.**(-7)*TFILM(J)**2 -
*          9.61487470533368*10.**(-10)*TFILM(J)**3 +
*          1.300855464242*10.**(-12)*TFILM(J)**4 -
*          7.009436103929*10.**(-16)*TFILM(J)**5

  IF (TSTEAM(J) .LE. 320) THEN
    VG(J)= 3.7765014695224E5 - 4.8166922018646E3 * TSTEAM(J)
*          + 2.30839950003999E1 * TSTEAM(J)**2
*          - 4.92547853988165E-2 * TSTEAM(J)**3
*          + 3.94711740176825E-5 * TSTEAM(J)**4
  ELSE
    VG(J)= 2.0944941102788E4 - 2.57511068255697E2 * TSTEAM(J)
*          + 1.26769945136484 * TSTEAM(J)**2
*          - 3.122098724905E-3 * TSTEAM(J)**3
*          + 3.84527176768464E-6 * TSTEAM(J)**4
*          - 1.89417409454379E-9 * TSTEAM(J)**5
      END IF


      HFG(J)= 5.138499737498*10.**6-2.88007195645*10.**4
*          * TSTEAM(J) + 1.387146790307*10.**2*TSTEAM(J)**2 -
*          3.6214603994528*10.**(-1)*TSTEAM(J)**3 +
*          4.776360304615*10.**(-4)*TSTEAM(J)**4 -
*          2.6171073275132*10.**(-7)*TSTEAM(J)**5

      CPF(J)= 5.49664984073512*10.**4-6.83922749835455*10.**2
*         *TFILM(J)+3.66613575502*TFILM(J)**2-9.774641549244E-3
*          * TFILM(J)**3 + 1.2944551269757E-5*TFILM(J)**4 -
*          6.78966872244218*10.**(-9)*TFILM(J)**5

      CPG(J)= -7.0138991625627*10.**(2)+3.10681344157*10.**(1)
*          * TSTEAM(J) - 1.43330809031838*10.**(-1)*TSTEAM(J)**2 +
*          3.102487339759*10.**(-4)*TSTEAM(J)**3 -
*          3.37533518371059*10.**(-7)*TSTEAM(J)**4 +
*          2.09976698784749*10.**(-10)*TSTEAM(J)**5

      UF(J)= 5.28866616855338*10.**(-1)-6.9064403925*10.**(-3)
*          * TFILM(J) + 3.6169015509742*10.**(-5)*TFILM(J)**2 -
*          9.475113986937*10.**(-8)*TFILM(J)**3 +
*          1.2401320526629*10.**(-10)*TFILM(J)**4 -
*          6.48230688486946*10.**(-14)*TFILM(J)**5

      UG(J)= -1.0493495919E-4 + 1.520614407775E-6
*          * TSTEAM(J) - 8.509310662084E-9 *TSTEAM(J) +
*          2.418828484978E-11 *TSTEAM(J)**3 -
*          3.39717932745E-14 *TSTEAM(J)**4 +
*          1.88340981436E-17 *TSTEAM(J)**5

      KF(J)= 7.60929710087 - 1.097443071183E-1 *TFILM(J) +
*          6.476232148521E-4 * TFILM(J)**2 -
*          1.83877277459E-6 *TFILM(J)**3 +
*          2.5564025355E-9 *TFILM(J)**4-1.4068703896348E-12
*          * TFILM(J)**5
```

```
          PRF(J)= 4.583467922E+3 - 6.00442918616E+1 *TFILM(J) +
     *  3.150508584456E-1*TFILM(J)**2 -8.2625902332188E-4*TFILM(J)**3
     *  +1.0820649955124E-6*TFILM(J)**4 -5.6571205177E-10*TFILM(J)**5

          SIGMA(J)= -2.11271594796 + 3.1290868968E-2 *TFILM(J) -
     * 1.76251989006E-4 *TFILM(J)**2 +4.91136030868E-7*TFILM(J)**3
     * -6.80272511265E-10*TFILM(J)**4 +3.742781911254E-13*TFILM(J)**5

         RHOF(J)= 1./VF(J)
         RHOG(J)= 1./VG(J)
         RHO(J)= RHOF(J) - RHOG(J)

C         WRITE(15,34)
C34       FORMAT(1X,T3,'TFILM',T13,'P',T22,'VF',T32,'VG',T41,'HFG',
C    *           T52,'CPF',T64,'CPG')
C         WRITE(15,35)
C35       FORMAT(1X,T3,'(K)',T11,'(KPA)',T20,'(M3/KG)',T30,'(M3/KG)',
C    *      T40,'(J/KG)',T51,'(J/(KG*K))',T62,'(J/(KG*K))')
C      WRITE(15,36) TFILM(J), P(J),VF(J),VG(J),HFG(J),CPF(J),CPG(J)
C36       FORMAT(1X,F6.2,T10,F7.3,T19,F8.6,T29,F7.2,T38,F10.2,T52,
C    *          F7.2,T64,F7.2)
C      WRITE(15,*)
C      WRITE(15,37)
C37    FORMAT (1X,T5,'UF',T16,'UG',T33,'KF',T46,'PRF',
CC   *          T55,'SIGMA')
C      WRITE (15,38)
C38    FORMAT (1X,T3,'(N*S/M2)',T14,'(N*S/M2)',
C    *         T30,'(W/M*K)',T55,'(N/M)')
C      WRITE (15,39) UF(J),UG(J),KF(J),PRF(J),SIGMA(J)
C39    FORMAT(1X,T2,F9.7,T13,F10.8,T31,F6.4,T45,F6.3,T55,F6.4)
C      WRITE (15,*)
C      WRITE (15,*)

      TOL= 1.0
      CH= 0.0
      DN1= .00193788
      HMF= 1.0

 51   IF (ABS(CH-HMF) .GE. TOL) THEN
        CH= HMF
        Z= (WC**1.5)*(CH/(A*KC))**.5
         X1= RA*Z
         X2= RB*Z

        Eta=((DSQRT(2.D0)/Z)/(1+R2C/R1))*((DBSI1(X1)*DBSK1(X2)-
     *        DBSI1(X2)*DBSK1(X1))/(DBSI1(X1)*DBSK0(X2)+DBSI0(X2)
     *         *DBSK1(X1)))
        AFT= NU*PI*D2*THICK
        LA= (PI*(D2**2-DR**2))/(4*D2)
        AU= NU*DR*SPACEB*PI
        AFS= (2*NU*PI*(D2**2-DR**2))/4.
        AEF= Eta*AFS + Eta*AFT + AU
        Y= 1.3*ETA*AFS/(AEF*LA**.25)+(ETA*AFT)/(AEF*D2**.25)+
     *       AU/(AEF*DR**.25)


         DE= (1/Y)**4.
         DF= ((1./DE)**.25)/(1./DN1)**.25

         HMF= 0.689*((KF(J)**3 * RHOF(J)**2 * G * HFG(J))
```

```
     *          / (UF(J)*DT(J,3)*DE))**.25

           HBKSMH= 0.689*((KF(J)**3*RHOF(J)**2*G*HFG(J))/
     *          (UF(J)*DR*DT(J,3)))**.25

           HNUSS= 0.728*(KF(J)/DE)*((RHOF(J)*(RHOF(J)-RHOG(J))*G*HFG(J)
     *          *DE**3)/(UF(J)*DT(J,3)*KF(J)))**.25

           HNSMH= 0.728*(KF(J)/DR)*((RHOF(J)*(RHOF(J)-RHOG(J))*G*HFG(J)
     *          *DR**3)/(UF(J)*DT(J,3)))**.25

      GO TO 51
      END IF
      WRITE (15,*)

      AO= PI* DR * LEN
C     WRITE(15,*) 'AEF:',AEF
C     WRITE(15,*) 'AO:',AO
      RATIO= AEF/AO
C     WRITE(15,*) 'ETA:',ETA
C     WRITE(15,*) 'Z:',Z
C     WRITE(15,*) 'HMF:',HMF
      ENH= HMF*RATIO/HNSMH


      hfm= hmf*ratio

C      WRITE (15,70)
C 70   FORMAT (1X,T6,'HO(EXP)',T19,'HBK',T29,'AEF/AO',T39,'DT')
C     WRITE (15,71) HO(J,4),HFM,RATIO,DT(J,3)
C71   FORMAT (1X,T4,F7.1,T14,F10.2,T28,F8.6,T39,F5.2)
C     WRITE(15,72)
C72   FORMAT(1X,T2,'HNUSS',T15,'ENH B&K',T39,'HBKSMH',
C    *  T51,'HNSMH')
C     WRITE(15,73) HNUSS,ENH,HBKSMH,HNSMH
C     WRITE(15,*) 'HO (EXP)=',HO(J,4)
C73   FORMAT(1X,F9.2,T15,F6.3,T36,F9.2,T48,F9.2)
      WRITE (15,*) 'HBK=',HFM
C     WRITE (15,*) 'SIGMA:',SIGMA(J)
      WRITE (15,*) 'ENH(B&K)=', ENH
C     WRITE (15,*) 'SPACING=', S
C35   CONTINUE
      phip(j)= sigma(j)*dcos(beta)/(rhof(j)*g*spacet*d2)
      if (phip(j) .gt. 0.5) then
         phi(j)= 0.0
      else
      PHI(J)= DACOS((4*SIGMA(J)*DCOS(BETA)/(RHOF(J)*G*SPACET*D2))-1)
      end if
c
      EPH(J)= 0.874+0.1991E-2*PHI(J)-0.2642E-1*PHI(J)**2
     *          +0.553E-3*PHI(J)**3 - 0.1363E-2*PHI(J)**4
C
      if (phi(j) .eq. 0.0) then
      ffi(j)= 1
      else

        IF (AREA .EQ. 3) THEN
          FFI(J)= 1
        END IF
```

```
          IF (AREA .EQ. 1) THEN

          FFI(J)=   (2*SIGMA(J)/(RHOF(J)*G*DR*W))*(TAN(PHI(J)/2.)/PHI(J))
          END IF
          IF (AREA .EQ. 2) THEN
          FFI(J)=   (2*SIGMA(J)/(RHOF(J)*G*DR*(R2-(R1+S/2))))*
     *         (TAN(PHI(J)/2.)/PHI(J))
      END IF
      end if

      IF(FFI(J) .GE. 1)   THEN
          ff(J)= 1
      else
          ff(j)= ffi(j)
      end if

      if (phi(j) .eq. 0.0) then
      fsi(j)= 1
      else
      fsi(J)=   (4*SIGMA(J)/(RHOF(J)*G*DR*SPACEB))*(TAN(PHI(J)/2.)
     *          /PHI(J))
      end if

      IF (FSI(J) .GE. 1) THEN
          fs(j)= 1
      else
          fs(j)= fsi(j)
      end if

      IF (AREA .NE. 1) THEN
          FS(J)= PHI(J) * S/2
      END IF


C     FOR PHI(J)< PI/2
      IF (phi(j) .eq. 0.0) then
        hv(j)= w
          IF (AREA .EQ. 2) THEN
           HV(J)= (R2-(R1+S/2))
          END IF

           IF (AREA .EQ. 3) THEN
           HV(J) = 0
           END IF
      else IF (PHI(J) .LE. (PI/2.)) then
           HV(J)=  W*PHI(J)/SIN(PHI(J))
           IF (AREA .EQ. 2) THEN
             HV(J) =(R2-(R1+S/2))*PHI(J)/SIN(PHI(J))
           END IF

           IF (AREA .EQ. 3) THEN
             HV(J)= 0
           END IF
C     FOR PHI(J)> PI/2
      ELSE
           HV(J)=  W*PHI(J)/(2.-SIN(PHI(J)))
           IF (AREA .EQ. 2) THEN
             HV(J) =(R2-(R1+S/2))*PHI(J)/(2.-SIN(PHI(J)))
           END IF
           IF (AREA .EQ. 3) THEN
```

```
            HV(J)= 0
          END IF
        END IF
C
        QT(J)=  (RHOF(J)*HFG(J)*KF(J)**3*DT(J,3)**3/UF(J)
     *       *(0.728**4*RHO(J)*G/D2+BT*SIGMA(J)/THICK**3))**.25
C
        IF (HV(J) .EQ. 0) THEN
          QF(J)= 0
        ELSE
          IF (AREA .EQ. 1) THEN
          QF(J)=  ((RHOF(J)*HFG(J)*KF(J)**3*DT(J,3)**3/UF(J))*((0.943**4
     *       *RHO(J)*G/HV(J))+BF*SIGMA(J)/W**3))**.25
          END IF
          IF (AREA .EQ. 2) THEN

          QF(J)=  ((RHOF(J)*HFG(J)*KF(J)**3*DT(J,3)**3/UF(J))*((0.943**4
     *       *RHO(J)*G/HV(J))+BF*SIGMA(J)/(R2-(R1+S/2))**3))**.25
          END IF
        END IF
        IF (AREA .EQ. 1) THEN

        Qs(J)=  ((RHOF(J)*HFG(J)*KF(J)**3*DT(J,3)**3/UF(J))*(EPH(J)**3*
     *       RHO(J)*G/DR+BS*SIGMA(J)/SPACEB**3))**.25
        ELSE

        Qs(J)=  ((RHOF(J)*HFG(J)*KF(J)**3*DT(J,3)**3/UF(J))*(EPH(J)**3*
     *       RHO(J)*G/(DR+S*(1-2/PI))+BS*SIGMA(J)/ S**3))**.25
        END IF
C
        Qnus(J)=  0.728*((RHOF(J)*HFG(J)*KF(J)**3*DT(J,3)**3/UF(J))
     *        *(RHO(J)*G/DR))**.25
C
        IF (AREA .EQ. 1) THEN
        QQF(J)=  PI*D2*THICK*QT(J)*ETA+(PHI(J)/PI)*(((1-FF(J))*PI*(D2**2-
     *       DR**2)/2.)*QF(J)*ETA+(1-FS(J))*PI*DR*B1*SPACEB*QS(J))
        ELSE
C
        QQF(J)=  PI*(2*R2)*THICK*QT(J)*ETA+(PHI(J)/PI)*(PI*2
     *       *(R2**2-(R1+S/2)**2.)*QF(J)*ETA+PI*2*(PI*S/2)*B1
     *        *(R1+S/2*(1-2/(PI)))*ETA*QS(J))
        END IF


CCCCCCCCC FOR ENHANCEMENT WITHOUT EFFICIENCY
C       QQF(J)=  PI*D2*THICK*QT(J)+(PHI(J)/PI)*(((1-FF(J))*PI*(D2**2-
C    *       DR**2)/2.)*QF(J)+(1-FS(J))*PI*DR*B1*SPACEB*QS(J))
C
        QQS(J)= PI*DR*(SPACEB+THICK)*Qnus(J)
C
C
        EDT(J)= QQF(J)/QQS(J)
C
        GT(J)= SIGMA(J)*DR/(RHO(J)*G*THICK**3)
C
        GS(J)=  SIGMA(J)*DR/(RHO(J)*G*SPACEB**3)
C
        GF(J)=  SIGMA(J)*DR/(RHO(J)*G*W**3)
C
```

```
      TF(J) =0
      IF (HV(J) .NE. 0) THEN
        TF(J)=  ((0.943/0.728)**4*DR/HV(J)+BF*GF(J)/0.728**4)**.25
      END IF
C
      TS(J)=  (EPH(J)**3/0.728**4+BS*GS(J)/0.728**4)**.25
C
      TT(J)=  (DR/D2+BT*GT(J)/0.728**4)**.25
C
      IF (AREA .EQ. 1) THEN
      EDTC(J)=(D2/DR)*THICK/(SPACEB+THICK)*TT(J)*ETA+PHI(J)/PI*(1-FF(J))
     *     *((D2**2-DR**2)/(2*DR*(SPACEB+THICK)))*TF(J)*ETA+PHI(J)/PI
     *     *(1-FS(J))*B1*(SPACEB/(SPACEB+THICK))*TS(J)
      ELSE
      EDTC(J)= QQF(J)/QQS(J)
      END IF
C
      QFF(J)= (QF(J)+QT(J)+QS(J))*NU

      AT= PI*D2*T
      AF(J)= (PHI(J)/PI)*((1-FF(J))*PI*(D2**2-DR**2)/2)
      As(j)= (1-fs(j))*pi*dr*B1*spaceb
      Atotal(j)= At+As(j)+Af(j)



      HS(J)= QS(J)/DT(J,3)
      HF(J)=  QQf(j)/(Atotal(j)*DT(j,3))
      HN(J)= EDTC(J)*QNUS(J)/DT(J,3)
      HR(J)=  QQF(J)/(PI*DR*(SPACEB+THICK)*DT(J,3))

C      WRITE(15,*) 'HN:',HN(J)
      WRITE(15,*) 'HO(ROSE):',HN(J)
C      WRITE(15,*) 'HR:',HR(J)
C     WRITE(15,*) 'EDT:', EDT(J)
      write(15,*)
C      WRITE(15,*) 'TOTAL SURFACE AREA:',ATOTAL(J)
C      WRITE(15,*) 'AREA OF TIP:',AT
C      WRITE(15,*) 'AREA OF FLANK:',AF(J)
C      WRITE(15,*) 'AREA OF SPACE:',AS(J)


C      WRITE(15,*) 'HS:',HS(J)
C     WRITE(15,*) 'ENHANCEMENT FROM HEAT FLUX:', QQF(J)/QQS(J)
C      WRITE(15,*) 'QNUSS:',QNUS(J)
      WRITE(15,*) 'Edtc:', EDTC(J)
C      WRITE(15,*) 'QQF:', QQF(J)
C      WRITE(15,*) 'QQS:', QQS(J)
C      WRITE(15,*) 'HEAT FLUX ON FIN FLANK QF:', QF(J)
C      WRITE(15,*) 'HEAT FLUX AT FIN INTERSPACING QS:', QS(J)
C      WRITE(15,*) 'HEAT FLUX AT FIN TIP QT:' , QT(J)
C     WRITE(15,*) 'FF:',FF(J)
C     WRITE(15,*) 'FFI:',FFI(J)
C     WRITE(15,*) 'FS:',FS(J)
C     WRITE(15,*) 'FSI:',FSI(J)
      WRITE(15,*) 'PHI:',PHI(J)
C     WRITE(15,*) 'HV:',HV(J)
C     WRITE(15,*) 'RHOG:',RHOG(J)
C     WRITE(15,*) 'RHOF:',RHOF(J)
```

```
CC    WRITE(15,*) 'RHO:',RHO(J)
C     WRITE(15,*) 'D2:',D2
C     WRITE(15,*) 'BETA:',BETA
      WRITE(15,*) 'SIGMA:',SIGMA(J)
C     WRITE(15,*) 'G:',G
C     WRITE(15,*) 'GT:',GT(J)
C     WRITE(15,*) 'GS:',GS(J)
C     WRITE(15,*) 'GF:',GF(J)
C     WRITE(15,*) 'DE:',DE
C     WRITE(15,*) 'DR:',DR
C     WRITE(15,*) 'TF:',TF(J)
C     WRITE(15,*) 'TS:',TS(J)
C     WRITE(15,*) 'TT:',TT(J)
C     WRITE(15,*) 'FIN THICKNESS:',THICK
C     WRITE(15,*) 'SPACING AT FIN BASE (S):',SPACEB
C     WRITE(15,*) 'FIN SPACING AT TIP (B):',SPACET
C     WRITE(15,*) 'FIN PITCH:',PITCH
C     WRITE(15,*) 'FIN HEIGHT (H):',W
      WRITE(15,*)
C     WRITE(15,*)
c     for surface area effect
      f1(j)= fs(j)
      f2(j)= ff(j)
c
      ARF(J)= (R1*SPACET*PHI(J)*(1-F1(J))+(R2**2-R1**2)*PHI(J)
     *    *(1-F2(J))+(PI*R2*THICK))/(PI*R1*(SPACET+THICK))
c
C     EARF(J)= (R1*SPACET*PHI(J)*(1-F1(J))*ETA+(R2**2-R1**2)*PHI(J)
C    *    *(1-F2(J))*ETA+(PI*R2*THICK))/(PI*R1*(SPACET+THICK))
c
      ATS(J)= (R1*SPACET+(R2**2-R1**2)+R2*THICK)/
     *        (r1*(spacet+thick))
c
      Atr(j)= (r2**2-(r1+.5*spacet)**2+.5*pi*spacet*(r1+.5*spacet*(1-
     *     (2/pi)))+r2*thick)/(r1*(spacet+thick))
c
      Ar(j)= ((r2**2-(r1+.5*spacet)**2)*(phi(j)/pi)+(r1+.5*spacet*
     *     (1-(2/pi)))*.5*spacet*phi(j)+r2*thick)/
     *     (r1*(spacet+thick))
c
C     EAR(J)= ((R2**2-(R1+.5*SPACET)**2)*(PHI(J)/PI)*ETA+(R1+.5*SPACET*
C    *     (1-(2/PI)))*.5*SPACET*PHI(J)*ETA+R2*THICK*ETA)/
C    *     (R1*(SPACET+THICK))
c
      RSA(j)= (Ats(j)-Atr(j))/Ats(j)
      IEAA(j)= (Ar(j)-Arf(j))/Arf(j)
      MAXENH(j)= IEAA(j)-RSA(j)
c
C     WRITE(15,*) 'FRACTION OF AREA BLANKED ON TOP F1:',F1(J)
C     WRITE(15,*) 'FRACTION OF AREA BLANKED ON FLANKS F2:',F2(J)
C     WRITE(15,*) 'ACTIVE AREA ENHANCEMENT RECTANGULAR-SECTON
C    *   FINS ARF:',ARF(J)
C     WRITE(15,*) 'ACTIVE AREA ENHANCEMENT FILLET RADIUS ROOT AR:',
C    *   AR(J)
C     WRITE(15,*) 'RECTANGULAR-SECTION FINS TOTAL SURFACE AREA
C    *   ENHANCEMENT ATS:',ATS(J)
C     WRITE(15,*) 'FILLET RADIUS TOTAL SURFACE AREA ENHANCEMENT
C    *   ATR:',ATR(J)
C     WRITE(15,*) 'REDUCTION IN ENHANCEMENT DUE TO THE LOST OF SURFACE
C    *   AREA (FROM FILLET ROOT):',RSA(J)
```

```
C     WRITE(15,*) 'INCREASE IN ENHANCEMENT DUE TO ACTIVE AREA:',IEAA(J)
C     WRITE(15,*) 'MAX ENHANCEMENT:',MAXENH(J)
C     WRITE(15,*) 'ACTIVE SURFACE AREA ENHANCEMENT RATIO (AR/ARF):'
C    *       ,AR(J)/ARF(J)
C     WRITE(15,*)
C     WRITE(15,*)
      WRITE(15,*) 'ETA:',ETA
      WRITE(15,*) 'EQN(34) =',ARF(J)
      WRITE(15,*) 'EQN(43) =',AR(J)
      WRITE(15,*) 'EQN(41) =',ATS(J)
      WRITE(15,*) 'EQN(42) =',ATR(J)
      WRITE(15,*) 'EQN(43)/EQN(34) =',(AR(J)/ARF(J))
C     WRITE(15,*) 'DR=',DR
C     WRITE(15,*) 'SIGMA=',SIGMA(J)
C     WRITE(15,*) 'RHOG:',RHOG(J)
C     WRITE(15,*) 'RHOF:',RHOF(J)
      WRITE(15,*) 'RHO:',RHO(J)
 10   CONTINUE
C       CLOSE(16)
C5    CONTINUE

      END
```

APPENDIX D. SAMPLE DATA RUNS

Table II contains the correlation information for the data runs contained in this Appendix. All the data runs were processed using the Petukhov-Popov [Ref. 33] inside heat transfer correlation. The data have been printed out in the short form format.

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : ATOD11
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SMOOTH TUBE
Tube material : COPPER
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.8344
Alpha (based on Nusselt (Tdel)) = 0.8298
Enhancement (q) = .968
Enhancement (Del-T) = .976

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.28	7.880E+03	9.583E+03	5.348E+05	55.81	99.98
2	3.75	7.874E+03	9.773E+03	5.264E+05	53.86	99.91
3	3.23	7.836E+03	9.978E+03	5.158E+05	51.69	100.03
4	2.70	7.704E+03	1.012E+04	4.965E+05	49.07	100.04
5	2.18	7.502E+03	1.030E+04	4.757E+05	46.20	100.04
6	1.66	7.804E+03	1.188E+04	4.815E+05	40.53	100.03
7	1.14	6.693E+03	1.096E+04	4.067E+05	37.10	99.82
8	1.14	6.685E+03	1.097E+04	4.113E+05	37.51	100.02
9	1.66	7.239E+03	1.064E+04	4.501E+05	42.31	99.90
10	2.18	7.493E+03	1.026E+04	4.693E+05	45.73	99.91
11	2.70	7.812E+03	1.028E+04	4.920E+05	47.88	100.01
12	3.22	7.985E+03	1.017E+04	5.041E+05	49.55	99.97
13	3.73	7.938E+03	9.814E+03	5.020E+05	51.15	100.04
14	4.25	8.082E+03	9.818E+03	5.112E+05	52.07	100.01

Least-Squares Line for Ho vs q curve:
Slope = 0.0000E+00
Intercept = 0.0000E+00

Least-squares line for q = a*delta-T^b
a = 2.6963E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file ATOD11

NOTE: 14 X-Y pairs were stored in data file

```
NOTE: Program name : DRPALL
      Data taken by               : COBB
      This analysis done on file : ATSMTH1
      This analysis includes end-fin effect
      Thermal conductivity        = 390.8 (W/m.K)
      Inside diameter, Di         = 12.70 (mm)
      Outside diameter, Do        = 14.38 (mm)
      This analysis uses the QUARTZ THERMOMETER readings
      Modified Petukhov-Popov coefficient   = 2.5000
      Using HEATEX insert inside tube
      Tube Enhancement     : SMOOTH TUBE
      Tube material        : COPPER
      Pressure condition : ATMOSPHERIC
      Nusselt theory is used for Ho

Ci (based on Petukhov-Popov)      =  2.8493
Alpha (based on Nusselt (Tdel)) =  0.8499
Enhancement (q)                   =  1.000
Enhancement (Del-T)               =  1.000
```

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.30	7.969E+03	9.744E+03	5.619E+05	57.67	99.96
2	3.77	7.920E+03	9.884E+03	5.537E+05	56.01	99.89
3	3.24	7.858E+03	1.007E+04	5.459E+05	54.20	99.95
4	2.72	7.708E+03	1.021E+04	5.330E+05	52.18	100.04
5	2.19	7.485E+03	1.038E+04	5.128E+05	49.38	99.89
6	1.67	7.128E+03	1.058E+04	4.860E+05	45.96	100.06
7	1.15	6.658E+03	1.116E+04	4.503E+05	40.35	100.13
8	1.15	6.677E+03	1.121E+04	4.497E+05	40.13	99.99
9	1.67	7.124E+03	1.055E+04	4.828E+05	45.74	100.01
10	2.19	7.470E+03	1.034E+04	5.079E+05	49.13	100.07
11	2.71	7.752E+03	1.026E+04	5.269E+05	51.34	100.10
12	3.24	7.914E+03	1.013E+04	5.390E+05	53.19	100.14
13	3.76	7.962E+03	9.907E+03	5.383E+05	54.33	100.12
14	4.28	8.070E+03	9.847E+03	5.442E+05	55.27	100.12

```
Least-Squares Line for Ho vs q curve:
  Slope      =  0.0000E+00
  Intercept  =  0.0000E+00

Least-squares line for q = a*delta-T^b
  a =  2.7388E+04
  b =  7.5000E-01


NOTE: 14 data points were stored in file ATSMTH1

NOTE: 14 X-Y pairs were stored in data file
```

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : ATSMTH3
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SMOOTH TUBE
Tube material : COPPER
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.7549
Alpha (based on Nusselt (Tdel)) = 0.8561
Enhancement (q) = 1.010
Enhancement (Del-T) = 1.007

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.30	7.882E+03	9.681E+03	5.583E+05	57.67	100.05
2	3.77	7.912E+03	9.944E+03	5.542E+05	55.74	100.13
3	3.24	7.886E+03	1.020E+04	5.473E+05	53.63	99.96
4	2.72	7.716E+03	1.032E+04	5.290E+05	51.25	99.96
5	2.19	7.480E+03	1.049E+04	5.117E+05	48.77	100.12
6	1.67	7.153E+03	1.079E+04	4.869E+05	45.14	100.14
7	1.15	6.631E+03	1.132E+04	4.472E+05	39.51	100.01
8	1.15	6.602E+03	1.124E+04	4.454E+05	39.64	100.03
9	1.67	7.120E+03	1.071E+04	4.844E+05	45.21	100.05
10	2.19	7.520E+03	1.056E+04	5.129E+05	48.55	100.14
11	2.72	7.766E+03	1.040E+04	5.298E+05	50.93	99.95
12	3.24	7.936E+03	1.026E+04	5.412E+05	52.73	99.88
13	3.76	8.015E+03	1.007E+04	5.449E+05	54.10	100.08
14	4.28	8.059E+03	9.904E+03	5.480E+05	55.33	100.13

Least-Squares Line for Ho vs q curve:
Slope = 0.0000E+00
Intercept = 0.0000E+00

Least-squares line for q = a*delta-T^b
a = 2.7624E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file ATSMTH3

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VTSMTH1
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SMOOTH TUBE
Tube material : COPPER
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.6957
Alpha (based on Nusselt (Tdel)) = 0.8127
Enhancement (q) = 1.004
Enhancement (Del-T) = 1.003

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.31	8.715E+03	1.107E+04	1.869E+05	16.89	48.60
2	1.15	6.985E+03	1.297E+04	1.429E+05	11.02	48.57
3	3.78	8.576E+03	1.115E+04	1.830E+05	16.41	48.56
4	1.68	7.504E+03	1.197E+04	1.567E+05	13.09	48.60
5	3.25	8.503E+03	1.143E+04	1.817E+05	15.90	48.65
6	2.20	7.971E+03	1.176E+04	1.671E+05	14.21	48.50
7	2.73	8.306E+03	1.163E+04	1.759E+05	15.13	48.56
8	2.73	8.348E+03	1.171E+04	1.761E+05	15.04	48.52
9	2.20	7.932E+03	1.168E+04	1.684E+05	14.42	48.78
10	3.25	8.515E+03	1.145E+04	1.831E+05	15.99	48.78
11	1.68	7.436E+03	1.180E+04	1.567E+05	13.28	48.81
12	3.78	8.615E+03	1.121E+04	1.840E+05	16.40	48.54
13	4.31	8.670E+03	1.100E+04	1.877E+05	17.07	48.78
14	1.15	6.765E+03	1.226E+04	1.438E+05	11.73	48.95

Least-Squares Line for Ho vs q curve:
Slope = 0.0000E+00
Intercept = 0.0000E+00

Least-squares line for q = a*delta-T^b
a = 2.2763E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file VTSMTH1

NOTE: 14 X-Y pairs were stored in data file

```
NOTE: Program name : DRPALL
      Data taken by                : COBB
      This analysis done on file : VTSMTH3
      This analysis includes end-fin effect
      Thermal conductivity       = 390.8 (W/m.K)
      Inside diameter, Di        = 12.70 (mm)
      Outside diameter, Do       = 14.38 (mm)
      This analysis uses the QUARTZ THERMOMETER readings
      Modified Petukhov-Popov coefficient   = 2.5000
      Using HEATEX insert inside tube
      Tube Enhancement    : SMOOTH TUBE
      Tube material       : COPPER
      Pressure condition : VACUUM
      Nusselt theory is used for Ho

Ci (based on Petukhov-Popov)      =  2.8599
Alpha (based on Nusselt (Tdel)) =  0.7971
Enhancement (q)                   =   .979
Enhancement (Del-T)               =   .984
```

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.32	8.411E+03	1.049E+04	1.981E+05	18.88	48.43
2	1.16	6.659E+03	1.157E+04	1.540E+05	13.31	48.89
3	3.79	8.316E+03	1.061E+04	1.969E+05	18.56	48.36
4	1.68	7.263E+03	1.116E+04	1.715E+05	15.37	48.70
5	3.27	8.144E+03	1.068E+04	1.979E+05	18.53	48.86
6	2.21	7.669E+03	1.096E+04	1.845E+05	16.83	48.81
7	2.74	7.931E+03	1.078E+04	1.920E+05	17.82	48.86
8	2.74	7.975E+03	1.086E+04	1.938E+05	17.85	48.98
9	2.21	7.657E+03	1.093E+04	1.841E+05	16.84	48.86
10	3.27	8.136E+03	1.067E+04	1.976E+05	18.53	48.88
11	1.68	7.311E+03	1.128E+04	1.733E+05	15.37	48.77
12	3.80	8.196E+03	1.043E+04	2.017E+05	19.34	48.80
13	1.16	6.734E+03	1.188E+04	1.629E+05	13.72	48.85
14	4.33	8.237E+03	1.024E+04	2.038E+05	19.91	48.80

```
Least-Squares Line for Ho vs q curve:
  Slope      =  0.0000E+00
  Intercept  =  0.0000E+00

Least-squares line for q = a*delta-T^b
  a =  2.2132E+04
  b =  7.5000E-01


NOTE: 14 data points were stored in file VTSMTH3

NOTE: 14 X-Y pairs were stored in data file
```

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT011
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : COPPER
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 3.0632
Alpha (based on Nusselt (Tdel)) = 2.0960
Enhancement (q) = 3.331
Enhancement (Del-T) = 2.466

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	0.63	8.659E+03	3.392E+04	5.849E+05	17.25	99.90
2	1.15	1.123E+04	2.893E+04	7.700E+05	26.62	99.86
3	1.68	1.303E+04	2.785E+04	8.946E+05	32.12	99.82
4	2.20	1.441E+04	2.753E+04	9.891E+05	35.93	99.99
5	2.72	1.543E+04	2.719E+04	1.059E+06	38.93	100.03
6	3.24	1.634E+04	2.722E+04	1.115E+06	40.97	99.90
7	3.23	1.539E+04	2.435E+04	1.002E+06	41.14	99.98
8	3.75	1.781E+04	2.872E+04	1.161E+06	40.41	100.10
9	4.27	1.840E+04	2.855E+04	1.194E+06	41.83	99.80
10	4.79	1.888E+04	2.835E+04	1.228E+06	43.32	100.02
11	4.79	1.893E+04	2.847E+04	1.234E+06	43.34	100.17
12	4.27	1.845E+04	2.863E+04	1.195E+06	41.74	100.01
13	3.75	1.788E+04	2.882E+04	1.158E+06	40.18	100.27
14	3.23	1.730E+04	2.942E+04	1.114E+06	37.86	99.97
15	2.71	1.628E+04	2.925E+04	1.049E+06	35.88	99.96
16	2.19	1.511E+04	2.933E+04	9.739E+05	33.21	100.09
17	1.67	1.381E+04	3.056E+04	8.953E+05	29.30	99.99
18	1.15	1.208E+04	3.332E+04	7.764E+05	23.30	99.94
19	0.62	9.546E+03	4.668E+04	6.062E+05	12.99	100.15

Least-squares line for q = a*delta-T^b
a = 7.0930E+04
b = 7.5000E-01

NOTE: 19 data points were stored in file AT011

NOTE: 19 X-Y pairs were stored in data file

```
NOTE: Program name : DRPALL
      Data taken by                 : COBB
      This analysis done on file : AT013
      This analysis includes end-fin effect
      Thermal conductivity        = 390.8 (W/m.K)
      Inside diameter, Di         = 12.70 (mm)
      Outside diameter, Do        = 13.88 (mm)
      This analysis uses the QUARTZ THERMOMETER readings
      Modified Petukhov-Popov coefficient   = 2.5000
      Using HEATEX insert inside tube
      Tube Enhancement    : RECTANGULAR FINNED TUBE
      Tube material       : COPPER
      Pressure condition : ATMOSPHERIC
      Nusselt theory is used for Ho

Ci (based on Petukhov-Popov)      =  3.1616
Alpha (based on Nusselt (Tdel)) =  2.2757
Enhancement (q)                   =  3.718
Enhancement (Del-T)               =  2.677
```

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	3.74	1.863E+04	3.000E+04	1.160E+06	38.67	100.07
2	4.25	1.926E+04	2.987E+04	1.195E+06	40.01	99.86
3	3.22	1.784E+04	3.002E+04	1.104E+06	36.78	100.05
4	2.70	1.731E+04	3.151E+04	1.075E+06	34.10	100.04
5	2.18	1.586E+04	3.097E+04	9.897E+05	31.96	99.89
6	1.66	1.599E+04	4.077E+04	1.005E+06	24.65	99.97
7	1.14	1.310E+04	3.907E+04	8.263E+05	21.15	100.16
8	1.15	1.224E+04	3.278E+04	7.864E+05	23.99	100.01
9	1.67	1.439E+04	3.224E+04	9.312E+05	28.89	100.05
10	2.19	1.644E+04	3.367E+04	1.058E+06	31.43	100.06
11	2.70	1.718E+04	3.134E+04	1.092E+06	34.85	99.97
12	3.22	1.814E+04	3.112E+04	1.155E+06	37.10	100.06
13	3.74	1.902E+04	3.119E+04	1.205E+06	38.63	99.88
14	4.26	1.955E+04	3.064E+04	1.225E+06	39.97	99.86

```
Least-squares line for q = a*delta-T^b
  a =  7.7229E+04
  b =  7.5000E-01


NOTE: 14 data points were stored in file AT013

NOTE: 14 X-Y pairs were stored in data file
```

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT021
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SHALLOW FILLET FINNED TUBE
Tube material : COPPER
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 3.2217
Alpha (based on Nusselt (Tdel)) = 1.4856
Enhancement (q) = 2.105
Enhancement (Del-T) = 1.748

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	0.63	7.581E+03	2.151E+04	5.080E+05	23.62	99.80
2	1.15	9.183E+03	1.839E+04	6.298E+05	34.25	99.90
3	1.67	1.061E+04	1.875E+04	7.227E+05	38.54	99.74
4	2.20	1.139E+04	1.835E+04	7.762E+05	42.29	99.81
5	2.72	1.225E+04	1.873E+04	8.302E+05	44.32	99.92
6	3.24	1.271E+04	1.853E+04	8.587E+05	46.34	99.97
7	3.76	1.330E+04	1.881E+04	8.890E+05	47.27	100.01
8	4.27	1.351E+04	1.848E+04	8.942E+05	48.39	100.12
9	4.53	1.364E+04	1.841E+04	8.921E+05	48.45	100.07
10	4.53	1.368E+04	1.848E+04	8.899E+05	48.17	99.95
11	4.26	1.356E+04	1.850E+04	8.755E+05	47.32	100.08
12	3.74	1.333E+04	1.871E+04	8.487E+05	45.37	99.98
13	3.22	1.312E+04	1.916E+04	8.279E+05	43.22	99.83
14	2.70	1.253E+04	1.905E+04	7.864E+05	41.28	100.06
15	2.18	1.199E+04	1.944E+04	7.472E+05	38.44	100.03
16	1.66	1.243E+04	2.415E+04	7.669E+05	31.75	100.11
17	1.14	1.019E+04	2.161E+04	6.269E+05	29.01	100.05
18	0.62	8.711E+03	2.958E+04	5.206E+05	17.60	100.12

Least-squares line for q = a*delta-T^b
a = 4.9231E+04
b = 7.5000E-01

NOTE: 18 data points were stored in file AT021

NOTE: 18 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT023
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SHALLOW FILLET FINNED TUBE
Tube material : COPPER
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.9461
Alpha (based on Nusselt (Tdel)) = 1.5213
Enhancement (q) = 2.173
Enhancement (Del-T) = 1.790

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.28	1.287E+04	1.787E+04	8.699E+05	48.67	99.86
2	3.74	1.296E+04	1.864E+04	8.401E+05	45.08	100.21
3	3.22	1.300E+04	1.960E+04	8.138E+05	41.52	100.11
4	2.69	1.275E+04	2.035E+04	7.749E+05	38.08	99.78
5	2.17	1.216E+04	2.073E+04	7.214E+05	34.79	100.13
6	1.65	1.136E+04	2.139E+04	6.516E+05	30.47	100.09
7	1.13	1.008E+04	2.228E+04	5.659E+05	25.40	100.18
8	1.14	9.931E+03	2.301E+04	6.357E+05	27.62	100.02
9	1.66	1.139E+04	2.227E+04	7.205E+05	32.36	99.82
10	2.18	1.228E+04	2.126E+04	7.553E+05	35.53	100.25
11	2.69	1.307E+04	2.102E+04	7.748E+05	36.85	100.00
12	3.19	1.377E+04	2.106E+04	7.875E+05	37.40	99.86
13	3.70	1.424E+04	2.083E+04	7.889E+05	37.86	100.04
14	4.20	1.458E+04	2.055E+04	7.683E+05	37.38	100.15

Least-squares line for q = a*delta-T^b
a = 5.0729E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT023

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT031
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : DEEP FILLET FINNED TUBE
Tube material : COPPER
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 3.0158
Alpha (based on Nusselt (Tdel)) = 1.8948
Enhancement (q) = 2.912
Enhancement (Del-T) = 2.229

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	0.63	8.419E+03	3.200E+04	5.734E+05	17.92	100.07
2	1.15	1.094E+04	2.790E+04	7.614E+05	27.28	100.20
3	1.68	1.250E+04	2.590E+04	8.543E+05	32.99	99.74
4	2.20	1.375E+04	2.548E+04	9.401E+05	36.89	99.95
5	2.72	1.466E+04	2.504E+04	9.914E+05	39.60	99.93
6	3.24	1.545E+04	2.494E+04	1.038E+06	41.63	99.81
7	3.76	1.600E+04	2.459E+04	1.068E+06	43.42	100.22
8	4.27	1.655E+04	2.454E+04	1.092E+06	44.50	100.29
9	4.79	1.694E+04	2.437E+04	1.105E+06	45.35	99.98
10	4.78	1.707E+04	2.456E+04	1.096E+06	44.61	99.89
11	4.26	1.690E+04	2.518E+04	1.075E+06	42.69	99.76
12	3.74	1.641E+04	2.528E+04	1.040E+06	41.14	100.13
13	3.22	1.588E+04	2.559E+04	9.960E+05	38.92	99.93
14	2.70	1.517E+04	2.590E+04	9.479E+05	36.60	99.90
15	2.18	1.423E+04	2.621E+04	8.896E+05	33.94	100.21
16	1.66	1.301E+04	2.682E+04	8.108E+05	30.23	100.10
17	1.14	1.127E+04	2.779E+04	6.987E+05	25.14	99.94
18	0.62	9.003E+03	3.600E+04	5.490E+05	15.25	99.86

Least-squares line for q = a*delta-T^b
a = 6.3826E+04
b = 7.5000E-01

NOTE: 18 data points were stored in file AT031

NOTE: 18 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT033
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : DEEP FILLET FINNED TUBE
Tube material : COPPER
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 3.0216
Alpha (based on Nusselt (Tdel)) = 1.8008
Enhancement (q) = 2.721
Enhancement (Del-T) = 2.119

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.27	1.576E+04	2.278E+04	1.022E+06	44.86	99.88
2	3.75	1.539E+04	2.303E+04	9.969E+05	43.29	100.08
3	3.23	1.508E+04	2.370E+04	9.698E+05	40.92	99.80
4	2.71	1.442E+04	2.399E+04	9 333E+05	38.90	99.90
5	2.19	1.349E+04	2.411E+04	8.786E+05	36.44	100.08
6	1.67	1.261E+04	2.563E+04	8.217E+05	32.05	100.05
7	1.15	1.112E+04	2.752E+04	7.197E+05	26.15	99.97
8	1.15	1.105E+04	2.743E+04	7.296E+05	26.59	100.18
9	1.67	1.256E+04	2.567E+04	8.320E+05	32.41	99.69
10	2.19	1.347E+04	2.423E+04	8.966E+05	37.00	100.00
11	2.71	1.435E+04	2.399E+04	9.566E+05	39.87	100.06
12	3.23	1.501E+04	2.371E+04	9.949E+05	41.96	99.85
13	3.75	1.563E+04	2.364E+04	1.026E+06	43.40	100.02
14	4.27	1.596E+04	2.322E+04	1.039E+06	44.75	99.82

Least-squares line for q = a*delta-T^b
a = 6.0352E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT033

NOTE: 14 X-Y pairs were stored in data file

```
NOTE: Program name : DRPALL
      Data taken by              : COBB
      This analysis done on file : AT061
      This analysis includes end-fin effect
      Thermal conductivity      =  55.3 (W/m.K)
      Inside diameter, Di       = 12.70 (mm)
      Outside diameter, Do      = 13.88 (mm)
      This analysis uses the QUARTZ THERMOMETER readings
      Modified Petukhov-Popov coefficient   = 2.5000
      Using HEATEX insert inside tube
      Tube Enhancement    : RECTANGULAR FINNED TUBE
      Tube material       : 90/10 CU/NI
      Pressure condition : ATMOSPHERIC
      Nusselt theory is used for Ho

Ci (based on Petukhov-Popov)     =  2.7938
Alpha (based on Nusselt (Tdel)) =  1.3004
Enhancement (q)                  =  1.763
Enhancement (Del-T)              =  1.530
```

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	0.63	6.424E+03	2.240E+04	4.455E+05	19.89	100.03
2	1.15	7.797E+03	1.811E+04	5.480E+05	30.26	99.73
3	1.68	8.800E+03	1.749E+04	6.133E+05	35.06	99.80
4	2.20	9.495E+03	1.725E+04	6.616E+05	38.36	99.96
5	2.72	1.005E+04	1.715E+04	6.886E+05	40.15	99.82
6	3.23	1.047E+04	1.703E+04	6.996E+05	41.08	100.06
7	3.75	1.096E+04	1.737E+04	7.222E+05	41.57	99.80
8	4.27	1.113E+04	1.710E+04	7.337E+05	42.91	99.80
9	4.79	1.124E+04	1.681E+04	7.406E+05	44.05	99.81
10	4.79	1.125E+04	1.684E+04	7.428E+05	44.11	100.00
11	4.27	1.106E+04	1.691E+04	7.276E+05	43.02	99.99
12	3.75	1.094E+04	1.729E+04	7.152E+05	41.37	99.88
13	3.23	1.070E+04	1.754E+04	6.962E+05	39.69	99.84
14	2.71	1.030E+04	1.766E+04	6.709E+05	37.98	99.80
15	2.19	9.747E+03	1.772E+04	6.365E+05	35.93	99.95
16	1.67	9.042E+03	1.796E+04	5.900E+05	32.86	99.92
17	1.15	8.043E+03	1.863E+04	5.267E+05	28.27	99.93
18	0.62	6.527E+03	2.187E+04	4.215E+05	19.28	99.89

```
Least-squares line for q = a*delta-T^b
  a =  4.3671E+04
  b =  7.5000E-01
```

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT063
This analysis includes end-fin effect
Thermal conductivity = 55.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : 90/10 CU/NI
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.5534
Alpha (based on Nusselt (Tdel)) = 1.2925
Enhancement (q) = 1.749
Enhancement (Del-T) = 1.521

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.29	1.067E+04	1.670E+04	7.452E+05	44.62	99.87
2	3.77	1.047E+04	1.692E+04	7.313E+05	43.22	100.10
3	3.24	1.021E+04	1.716E+04	7.084E+05	41.28	100.03
4	2.72	9.886E+03	1.754E+04	6.835E+05	38.97	100.01
5	2.20	9.330E+03	1.760E+04	6.413E+05	36.43	100.08
6	1.67	8.658E+03	1.803E+04	5.902E+05	32.73	99.94
7	1.15	7.810E+03	1.971E+04	5.289E+05	26.84	99.93
8	1.15	7.811E+03	1.972E+04	5.297E+05	26.85	99.95
9	1.67	8.627E+03	1.792E+04	5.908E+05	32.96	100.02
10	2.20	9.282E+03	1.743E+04	6.368E+05	36.54	99.98
11	2.72	9.795E+03	1.723E+04	6.740E+05	39.12	100.05
12	3.24	1.016E+04	1.699E+04	6.977E+05	41.06	99.96
13	3.76	1.034E+04	1.653E+04	7.099E+05	42.94	99.94
14	4.28	1.057E+04	1.641E+04	7.249E+05	44.18	100.01

Least-squares line for q = a*delta-T^b
a = 4.3316E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT063

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT071
This analysis includes end-fin effect
Thermal conductivity = 14.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : DEEP FILLET FINNED TUBE
Tube material : STAINLESS-STEEL
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.2578
Alpha (based on Nusselt (Tdel)) = 1.0063
Enhancement (q) = 1.252
Enhancement (Del-T) = 1.184

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.31	6.915E+03	1.332E+04	4.995E+05	37.51	100.02
2	3.78	6.849E+03	1.362E+04	4.945E+05	36.31	100.02
3	3.25	6.786E+03	1.411E+04	4.887E+05	34.64	99.98
4	2.73	6.547E+03	1.407E+04	4.698E+05	33.38	99.95
5	2.20	6.344E+03	1.459E+04	4.536E+05	31.10	100.00
6	1.68	5.950E+03	1.483E+04	4.254E+05	28.68	100.09
7	1.15	5.377E+03	1.542E+04	3.816E+05	24.75	100.01
8	1.15	5.385E+03	1.550E+04	3.827E+05	24.68	100.03
9	1.68	5.962E+03	1.492E+04	4.267E+05	28.60	100.06
10	2.20	6.370E+03	1.475E+04	4.573E+05	31.00	100.01
11	2.73	6.587E+03	1.427E+04	4.739E+05	33.21	99.97
12	3.25	6.852E+03	1.439E+04	4.932E+05	34.27	100.01
13	3.78	6.918E+03	1.389E+04	4.991E+05	35.93	100.08
14	4.30	6.991E+03	1.359E+04	5.026E+05	36.98	100.04

Least-squares line for q = a*delta-T^b
a = 3.4145E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT071

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL

Data taken by : COBB

This analysis done on file : AT081

This analysis includes end-fin effect

Thermal conductivity = 14.3 (W/m.K)

Inside diameter, Di = 12.70 (mm)

Outside diameter, Do = 14.38 (mm)

This analysis uses the QUARTZ THERMOMETER readings

Modified Petukhov-Popov coefficient = 2.5000

Using HEATEX insert inside tube

Tube Enhancement : SHALLOW FILLET FINNED TUBE

Tube material : STAINLESS-STEEL

Pressure condition : ATMOSPHERIC

Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.3495

Alpha (based on Nusselt (Tdel)) = 0.9812

Enhancement (q) = 1.211

Enhancement (Del-T) = 1.154

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.32	6.080E+03	1.328E+04	4.498E+05	33.87	99.99
2	3.79	6.059E+03	1.371E+04	4.439E+05	32.38	99.89
3	3.26	5.968E+03	1.398E+04	4.366E+05	31.24	99.93
4	2.73	5.805E+03	1.408E+04	4.239E+05	30.10	100.03
5	2.21	5.596E+03	1.429E+04	4.067E+05	28.47	99.97
6	1.68	5.320E+03	1.477E+04	3.860E+05	26.13	100.14
7	1.15	4.859E+03	1.539E+04	3.495E+05	22.72	99.99
8	1.15	4.859E+03	1.538E+04	3.496E+05	22.73	100.05
9	1.68	5.318E+03	1.475E+04	3.851E+05	26.10	100.01
10	2.21	5.648E+03	1.462E+04	4.102E+05	28.05	100.02
11	2.73	5.884E+03	1.453E+04	4.271E+05	29.40	99.99
12	3.26	6.036E+03	1.433E+04	4.391E+05	30.65	100.03
13	3.78	6.096E+03	1.387E+04	4.437E+05	31.99	100.03
14	4.31	6.228E+03	1.394E+04	4.527E+05	32.47	100.10

Least-squares line for q = a*delta-T^b

a = 3.3221E+04

b = 7.5000E-01

NOTE: 14 data points were stored in file AT081

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT041
This analysis includes end-fin effect
Thermal conductivity = 55.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : DEEP FILLET FINNED TUBE
Tube material : 90/10 CU/NI
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.6453
Alpha (based on Nusselt (Tdel)) = 1.0511
Enhancement (q) = 1.327
Enhancement (Del-T) = 1.237

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.28	9.100E+03	1.295E+04	6.161E+05	47.56	100.12
2	3.75	9.035E+03	1.321E+04	6.015E+05	45.52	99.92
3	3.23	8.924E+03	1.351E+04	5.889E+05	43.59	99.94
4	2.70	8.680E+03	1.368E+04	5.654E+05	41.34	99.92
5	2.18	8.328E+03	1.385E+04	5.374E+05	38.80	99.97
6	1.66	7.897E+03	1.434E+04	[illegible].068E+05	35.34	100.17
7	1.14	7.133E+03	1.490E+04	4.539E+05	30.47	100.04
8	1.14	7.136E+03	1.490E+04	4.540E+05	30.46	100.06
9	1.66	8.875E+03	1.790E+04	5.660E+05	31.62	100.02
10	2.18	8.434E+03	1.410E+04	5.373E+05	38.09	99.96
11	1.66	7.871E+03	1.421E+04	4.987E+05	35.10	100.10
12	2.70	8.735E+03	1.374E+04	5.547E+05	40.36	99.92
13	3.22	9.049E+03	1.371E+04	5.736E+05	41.84	99.82
14	3.74	9.203E+03	1.347E+04	5.827E+05	43.25	99.99

Least-squares line for q = a*delta-T^b
a = 3.5192E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT041

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : ORPALL
Data taken by : COBB
This analysis done on file : AT051
This analysis includes end-fin effect
Thermal conductivity = 55.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SHALLOW FILLET FINNED TUBE
Tube material : 90/10 CU/NI
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.6676
Alpha (based on Nusselt (Tdel)) = 1.0605
Enhancement (q) = 1.343
Enhancement (Del-T) = 1.248

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qo (W/m^2)	Tcf (C)	Ts (C)
1	4.30	8.577E+03	1.288E+04	6.138E+05	47.65	100.17
2	3.78	8.491E+03	1.313E+04	6.061E+05	46.17	99.87
3	3.25	8.393E+03	1.349E+04	6.016E+05	44.61	100.12
4	2.73	8.115E+03	1.358E+04	5.824E+05	42.87	99.92
5	2.21	7.747E+03	1.370E+04	5.582E+05	40.73	100.13
6	1.68	7.366E+03	1.436E+04	5.301E+05	36.92	100.13
7	1.15	6.646E+03	1.502E+04	4.757E+05	31.68	99.96
8	1.15	6.648E+03	1.503E+04	4.778E+05	31.78	100.18
9	1.68	7.331E+03	1.428E+04	5.315E+05	37.22	100.01
10	2.21	7.823E+03	1.399E+04	5.686E+05	40.65	100.07
11	2.73	8.125E+03	1.366E+04	5.910E+05	43.28	100.04
12	3.26	8.373E+03	1.347E+04	6.063E+05	45.00	99.96
13	3.78	8.568E+03	1.334E+04	6.194E+05	46.43	99.99
14	4.31	8.685E+03	1.315E+04	6.274E+05	47.70	99.98

Least-squares line for q = a*delta-T^b
a = 3.4918E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT051

NOTE: 14 X-Y pairs were stored in data file

```
NOTE: Program name : DRPALL
      Data taken by              : COBB
      This analysis done on file : AT091
      This analysis includes end-fin effect
      Thermal conductivity      =  14.3 (W/m.K)
      Inside diameter, Di       = 12.70 (mm)
      Outside diameter, Do      = 13.88 (mm)
      This analysis uses the QUARTZ THERMOMETER readings
      Modified Petukhov-Popov coefficient   = 2.5000
      Using HEATEX insert inside tube
      Tube Enhancement    : RECTANGULAR FINNED TUBE
      Tube material       : STAINLESS-STEEL
      Pressure condition : ATMOSPHERIC
      Nusselt theory is used for Ho

Ci (based on Petukhov-Popov)      =  2.1128
Alpha (based on Nusselt (Tdel)) =  1.0062
Enhancement (q)                   =  1.252
Enhancement (Del-T)               =  1.184
```

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.25	7.158E+03	1.419E+04	4.434E+05	31.24	99.98
2	3.72	7.015E+03	1.420E+04	4.311E+05	30.35	100.04
3	3.20	6.896E+03	1.446E+04	4.196E+05	29.02	100.20
4	2.70	6.719E+03	1.492E+04	4.268E+05	28.61	99.98
5	2.18	6.329E+03	1.463E+04	4.081E+05	27.89	99.87
6	1.66	5.923E+03	1.495E+04	3.905E+05	26.11	100.03
7	1.14	5.399E+03	1.617E+04	3.565E+05	22.05	99.79
8	1.15	5.390E+03	1.618E+04	3.604E+05	22.28	100.07
9	1.67	5.932E+03	1.521E+04	4.021E+05	26.44	99.99
10	2.19	6.318E+03	1.486E+04	4.320E+05	29.07	99.98
11	2.72	6.664E+03	1.500E+04	4.596E+05	30.64	99.99
12	3.24	6.858E+03	1.474E+04	4.753E+05	32.24	99.96
13	3.77	6.991E+03	1.448E+04	4.874E+05	33.66	99.95
14	4.29	7.087E+03	1.423E+04	4.941E+05	34.73	99.77

```
Least-squares line for q = a*delta-T^b
  a =  3.4378E+04
  b =  7.5000E-01


NOTE: 14 data points were stored in file AT091

NOTE: 14 X-Y pairs were stored in data file
```

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT094
This analysis includes end-fin effect
Thermal conductivity = 14.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : STAINLESS-STEEL
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.0961
Alpha (based on Nusselt (Tdel)) = 1.1333
Enhancement (q) = 1.468
Enhancement (Del-T) = 1.333

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.29	7.491E+03	1.602E+04	5.248E+05	32.76	99.99
2	3.77	7.354E+03	1.621E+04	5.147E+05	31.74	99.91
3	3.24	7.216E+03	1.662E+04	5.045E+05	30.35	100.01
4	2.72	6.956E+03	1.673E+04	4.853E+05	29.01	99.92
5	2.20	6.563E+03	1.654E+04	4.573E+05	27.65	99.95
6	1.67	6.158E+03	1.718E+04	4.287E+05	24.96	99.96
7	1.15	5.566E+03	1.861E+04	3.843E+05	20.65	99.81
8	1.15	5.567E+03	1.865E+04	3.851E+05	20.65	99.81
9	1.67	6.182E+03	1.739E+04	4.326E+05	24.88	100.15
10	2.20	6.608E+03	1.687E+04	4.631E+05	27.46	99.96
11	2.72	6.948E+03	1.673E+04	4.879E+05	29.17	99.89
12	3.25	7.212E+03	1.664E+04	5.085E+05	30.56	100.09
13	3.77	7.339E+03	1.617E+04	5.173E+05	32.00	100.02
14	4.29	7.506E+03	1.610E+04	5.275E+05	32.76	99.95

Least-squares line for q = a*delta-T^b
a = 3.8769E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT094

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT101
This analysis includes end-fin effect
Thermal conductivity = 231.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : ALUMINUM
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.3854
Alpha (based on Nusselt (Tdel)) = 1.7846
Enhancement (q) = 2.688
Enhancement (Del-T) = 2.100

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.27	1.470E+04	2.360E+04	9.614E+05	40.74	100.00
2	3.75	1.414E+04	2.358E+04	9.293E+05	39.42	100.01
3	3.23	1.359E+04	2.389E+04	8.995E+05	37.65	100.12
4	2.71	1.288E+04	2.420E+04	8.546E+05	35.31	99.92
5	2.19	1.197E+04	2.456E+04	7.973E+05	32.46	99.91
6	1.67	1.091E+04	2.572E+04	7.292E+05	28.35	99.95
7	1.15	9.571E+03	2.923E+04	6.394E+05	21.88	100.11
8	1.15	9.581E+03	2.967E+04	6.466E+05	21.80	100.02
9	1.67	1.082E+04	2.558E+04	7.393E+05	28.90	99.98
10	2.20	1.192E+04	2.462E+04	8.138E+05	33.05	100.14
11	2.72	1.297E+04	2.476E+04	8.834E+05	35.68	100.15
12	3.24	1.371E+04	2.449E+04	9.286E+05	37.92	100.05
13	3.76	1.440E+04	2.449E+04	9.722E+05	39.69	100.10
14	4.28	1.491E+04	2.435E+04	1.007E+06	41.37	100.09

Least-squares line for q = a*delta-T^b
a = 6.0336E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT101

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT103
This analysis includes end-fin effect
Thermal conductivity = 231.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : ALUMINUM
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.2017
Alpha (based on Nusselt (Tdel)) = 1.6987
Enhancement (q) = 2.517
Enhancement (Del-T) = 1.998

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.27	1.408E+04	2.306E+04	9.330E+05	40.45	100.02
2	3.75	1.362E+04	2.315E+04	8.836E+05	38.16	100.09
3	3.22	1.316E+04	2.353E+04	8.345E+05	35.47	100.12
4	2.70	1.248E+04	2.375E+04	7.741E+05	32.59	99.85
5	2.18	1.170E+04	2.453E+04	7.245E+05	29.54	99.85
6	1.66	1.066E+04	2.573E+04	6.608E+05	25.68	100.14
7	1.14	9.217E+03	2.823E+04	5.682E+05	20.13	100.07
8	1.14	9.222E+03	2.827E+04	5.683E+05	20.10	100.06
9	1.66	1.062E+04	2.557E+04	6.583E+05	25.74	99.86
10	2.18	1.171E+04	2.453E+04	7.250E+05	29.55	99.97
11	2.70	1.262E+04	2.421E+04	7.822E+05	32.31	100.02
12	3.21	1.322E+04	2.353E+04	8.163E+05	34.69	100.09
13	3.73	1.378E+04	2.325E+04	8.471E+05	36.43	100.02
14	4.25	1.419E+04	2.291E+04	8.689E+05	37.92	99.92

Least-squares line for q = a*delta-T^b
a = 5.7722E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT103

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT112
This analysis includes end-fin effect
Thermal conductivity = 231.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : DEEP FILLET FINNED TUBE
Tube material : ALUMINUM
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.3321
Alpha (based on Nusselt (Tdel)) = 1.5622
Enhancement (q) = 2.251
Enhancement (Del-T) = 1.838

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.29	1.286E+04	1.968E+04	8.979E+05	45.63	99.97
2	3.77	1.263E+04	2.018E+04	8.767E+05	43.45	100.01
3	3.24	1.227E+04	2.062E+04	8.424E+05	40.85	99.87
4	2.72	1.174E+04	2.101E+04	8.019E+05	38.17	100.08
5	2.19	1.107E+04	2.158E+04	7.487E+05	34.69	100.04
6	1.67	1.017E+04	2.253E+04	6.820E+05	30.27	100.04
7	1.15	8.897E+03	2.453E+04	5.908E+05	24.09	99.99
8	1.15	8.884E+03	2.443E+04	5.903E+05	24.16	100.03
9	1.67	1.016E+04	2.243E+04	6.791E+05	30.27	100.06
10	2.19	1.110E+04	2.161E+04	7.422E+05	34.35	99.97
11	2.71	1.187E+04	2.125E+04	7.926E+05	37.30	99.93
12	3.23	1.248E+04	2.102E+04	8.345E+05	39.69	100.07
13	3.75	1.292E+04	2.067E+04	8.574E+05	41.48	99.99
14	4.26	1.324E+04	2.021E+04	8.578E+05	42.44	99.99

Least-squares line for q = a*delta-T^b
a = 5.2515E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file AT112

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : AT131
This analysis includes end-fin effect
Thermal conductivity = 231.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SHALLOW FILLET FINNED TUBE
Tube material : ALUMINUM
Pressure condition : ATMOSPHERIC
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.2509
Alpha (based on Nusselt (Tdel)) = 1.4417
Enhancement (q) = 2.023
Enhancement (Del-T) = 1.696

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.27	1.205E+04	1.853E+04	7.870E+05	42.48	100.06
2	3.75	1.182E+04	1.894E+04	7.662E+05	40.45	99.91
3	3.74	1.181E+04	1.891E+04	7.654E+05	40.47	99.95
4	3.22	1.148E+04	1.933E+04	7.419E+05	38.38	100.07
5	2.70	1.094E+04	1.956E+04	7.056E+05	36.07	99.93
6	2.18	1.028E+04	1.996E+04	6.622E+05	33.18	100.01
7	1.66	9.399E+03	2.053E+04	6.021E+05	29.32	100.01
8	1.14	8.302E+03	2.270E+04	5.303E+05	23.36	100.08
9	1.14	8.303E+03	2.275E+04	5.314E+05	23.36	100.03
10	1.66	9.401E+03	2.062E+04	6.062E+05	29.40	99.93
11	2.18	1.033E+04	2.020E+04	6.690E+05	33.12	99.95
12	2.71	1.090E+04	1.949E+04	7.090E+05	36.38	100.03
13	3.23	1.149E+04	1.942E+04	7.480E+05	38.51	100.01
14	3.75	1.180E+04	1.892E+04	7.681E+05	40.59	99.95
15	4.26	1.211E+04	1.865E+04	7.863E+05	42.15	99.99

Least-squares line for q = a*delta-T^b
a = 4.8156E+04
b = 7.5000E-01

NOTE: 15 data points were stored in file AT131

NOTE: 15 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT011
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : COPPER
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.9862
Alpha (based on Nusselt (Tdel)) = 1.5005
Enhancement (q) = 2.275
Enhancement (Del-T) = 1.853

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	2.21	1.209E+04	2.122E+04	2.843E+05	13.40	48.54
2	0.63	7.899E+03	2.965E+04	1.779E+05	6.00	48.69
3	1.16	1.007E+04	2.465E+04	2.317E+05	9.40	48.20
4	0.63	7.724E+03	2.754E+04	1.751E+05	6.36	48.47
5	1.69	1.127E+04	2.240E+04	2.722E+05	12.15	48.86
6	2.74	1.328E+04	2.222E+04	3.184E+05	14.33	48.49
7	3.27	1.367E+04	2.142E+04	3.316E+05	15.48	48.73
8	3.80	1.455E+04	2.212E+04	3.426E+05	15.49	48.31
9	4.32	1.466E+04	2.131E+04	3.485E+05	16.35	48.67
10	4.85	1.502E+04	2.122E+04	3.551E+05	16.74	48.78
11	4.32	1.431E+04	2.055E+04	3.315E+05	16.13	48.22
12	3.79	1.439E+04	2.171E+04	3.325E+05	15.31	48.35
13	3.27	1.386E+04	2.183E+04	3.286E+05	15.05	48.81
14	2.74	1.322E+04	2.200E+04	3.093E+05	14.06	48.49
15	2.21	1.244E+04	2.232E+04	2.909E+05	13.03	48.55
16	1.68	1.134E+04	2.260E+04	2.647E+05	11.71	48.49
17	1.16	9.904E+03	2.362E+04	2.334E+05	9.88	48.98
18	1.16	9.773E+03	2.293E+04	2.360E+05	10.29	49.37
19	1.69	1.172E+04	2.417E+04	2.820E+05	11.66	49.10

Least-squares line for q = a*delta-T^b
a = 4.2752E+04
b = 7.5000E-01

NOTE: 19 data points were stored in file VT011

NOTE: 19 X-Y pairs were stored in data file

```
NOTE: Program name : DRPALL
      Data taken by              : COBB
      This analysis done on file : VT021
      This analysis includes end-fin effect
      Thermal conductivity      = 390.8 (W/m.K)
      Inside diameter, Di       = 12.70 (mm)
      Outside diameter, Do      = 14.38 (mm)
      This analysis uses the QUARTZ THERMOMETER readings
      Modified Petukhov-Popov coefficient   = 2.5000
      Using HEATEX insert inside tube
      Tube Enhancement    : SHALLOW FILLET FINNED TUBE
      Tube material       : COPPER
      Pressure condition : VACUUM
      Nusselt theory is used for Ho

Ci (based on Petukhov-Popov)     =  2.7942
Alpha (based on Nusselt (Tdel)) =  1.1491
Enhancement (q)                 =  1.594
Enhancement (Del-T)             =  1.419
```

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	0.63	6.616E+03	2.125E+04	1.586E+05	7.46	48.91
2	1.16	8.435E+03	1.901E+04	2.062E+05	10.85	48.66
3	1.69	9.253E+03	1.710E+04	2.302E+05	13.46	48.78
4	2.22	9.770E+03	1.612E+04	2.462E+05	15.27	48.97
5	2.74	1.043E+04	1.623E+04	2.594E+05	15.98	48.65
6	3.26	1.109E+04	1.649E+04	2.532E+05	15.35	48.35
7	4.84	1.191E+04	1.611E+04	2.699E+05	16.75	48.78
8	4.84	1.199E+04	1.624E+04	2.625E+05	16.16	48.45
9	4.31	1.181E+04	1.638E+04	2.526E+05	15.42	48.71
10	3.77	1.162E+04	1.660E+04	2.371E+05	14.28	48.85
11	4.29	1.183E+04	1.634E+04	2.334E+05	14.28	48.85
12	3.76	1.172E+04	1.673E+04	2.196E+05	13.13	48.87
13	3.24	1.160E+04	1.731E+04	2.088E+05	12.06	48.57
14	2.72	1.108E+04	1.728E+04	1.986E+05	11.49	48.94
15	2.19	1.070E+04	1.803E+04	1.816E+05	10.07	48.56
16	1.67	1.007E+04	1.895E+04	1.647E+05	8.70	48.60
17	1.14	8.770E+03	1.911E+04	1.409E+05	7.37	48.79
18	0.62	6.931E+03	2.135E+04	1.078E+05	5.05	48.92

```
Least-squares line for q = a*delta-T^b
  a =  3.2492E+04
  b =  7.5000E-01


NOTE: 18 data points were stored in file VT021

NOTE: 18 X-Y pairs were stored in data file
```

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT023
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SHALLOW FILLET FINNED TUBE
Tube material : COPPER
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 3.0216
Alpha (based on Nusselt (Tdel)) = 1.1247
Enhancement (q) = 1.549
Enhancement (Del-T) = 1.388

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	1.13	1.019E+04	2.309E+04	9.572E+04	4.15	48.82
2	1.65	1.129E+04	2.111E+04	1.076E+05	5.10	48.96
3	2.17	1.269E+04	2.209E+04	1.168E+05	5.29	48.64
4	2.68	1.309E+04	2.089E+04	1.206E+05	5.77	48.81
5	3.20	1.374E+04	2.094E+04	1.263E+05	6.03	48.88
6	3.71	1.453E+04	2.150E+04	1.217E+05	5.66	48.54
7	4.23	1.434E+04	2.021E+04	1.192E+05	5.90	48.87
8	4.25	1.334E+04	1.847E+04	1.711E+05	9.27	48.79
9	3.73	1.336E+04	1.921E+04	1.612E+05	8.39	48.71

Least-squares line for q = a*delta-T^b
a = 3.2541E+04
b = 7.5000E-01

NOTE: 09 data points were stored in file VT023

NOTE: 09 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT031
This analysis includes end-fin effect
Thermal conductivity = 390.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : DEEP FILLET FINNED TUBE
Tube material : COPPER
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 3.0312
Alpha (based on Nusselt (Tdel)) = 1.2910
Enhancement (q) = 1.862
Enhancement (Del-T) = 1.594

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	0.63	7.685E+03	2.547E+04	1.647E+05	6.47	48.55
2	1.15	9.431E+03	2.040E+04	2.035E+05	9.98	48.72
3	1.68	1.076E+04	1.986E+04	2.274E+05	11.45	48.54
4	2.19	1.177E+04	1.930E+04	1.881E+05	9.75	48.67
5	2.71	1.243E+04	1.908E+04	1.990E+05	10.43	48.95
6	4.80	1.501E+04	2.068E+04	2.508E+05	12.13	48.58
7	4.27	1.485E+04	2.107E+04	2.395E+05	11.37	48.51
8	3.75	1.418E+04	2.053E+04	2.222E+05	10.83	48.98
9	3.22	1.411E+04	2.149E+04	2.062E+05	9.59	48.54
10	2.70	1.326E+04	2.099E+04	1.909E+05	9.09	48.70
11	3.22	1.412E+04	2.147E+04	1.988E+05	9.26	48.68
12	3.75	1.458E+04	2.139E+04	2.238E+05	10.46	48.51
13	4.27	1.479E+04	2.089E+04	2.233E+05	10.69	48.50
14	4.79	1.512E+04	2.081E+04	2.306E+05	11.08	48.57
15	0.62	7.733E+03	2.403E+04	1.336E+05	5.56	48.91
16	1.15	9.971E+03	2.238E+04	1.802E+05	8.05	48.38
17	1.67	1.106E+04	2.057E+04	2.077E+05	10.10	48.40
18	2.20	1.180E+04	1.975E+04	2.344E+05	11.87	48.72

Least-squares line for q = a*delta-T^b
a = 3.7202E+04
b = 7.5000E-01

NOTE: 18 data points were stored in file VT031

NOTE: 18 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT041
This analysis includes end-fin effect
Thermal conductivity = 55.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : DEEP FILLET FINNED TUBE
Tube material : 90/10 CU/NI
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.4826
Alpha (based on Nusselt (Tdel)) = 0.8597
Enhancement (q) = 1.083
Enhancement (Del-T) = 1.061

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.28	9.181E+03	1.339E+04	1.561E+05	11.66	48.64
2	3.75	9.230E+03	1.397E+04	1.508E+05	10.80	48.67
3	3.23	8.901E+03	1.383E+04	1.421E+05	10.28	48.84
4	2.71	8.690E+03	1.416E+04	1.343E+05	9.48	48.87
5	2.18	8.262E+03	1.424E+04	1.267E+05	8.90	49.01
6	4.27	9.272E+03	1.356E+04	1.546E+05	11.40	48.97
7	3.75	9.012E+03	1.345E+04	1.401E+05	10.42	48.61
8	1.14	7.034E+03	1.571E+04	1.041E+05	6.62	48.52
9	1.66	7.751E+03	1.466E+04	1.158E+05	7.90	48.61
10	1.14	7.067E+03	1.583E+04	1.029E+05	6.50	48.67
11	1.66	7.862E+03	1.502E+04	1.134E+05	7.55	48.46
12	2.18	8.397E+03	1.462E+04	1.207E+05	8.26	48.55
13	2.70	8.726E+03	1.422E+04	1.255E+05	8.83	48.64
14	3.22	9.114E+03	1.429E+04	1.296E+05	9.07	48.57

Least-squares line for q = a*delta-T^b
a = 2.4813E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file VT041

NOTE: 14 X-Y pairs were stored in data file

```
NOTE: Program name : DRPALL
      Data taken by              : COBB
      This analysis done on file : VT051
      This analysis includes end-fin effect
      Thermal conductivity       =  55.3 (W/m.K)
      Inside diameter, Di        = 12.70 (mm)
      Outside diameter, Do       = 14.38 (mm)
      This analysis uses the QUARTZ THERMOMETER readings
      Modified Petukhov-Popov coefficient   = 2.5000
      Using HEATEX insert inside tube
      Tube Enhancement    : SHALLOW FILLET FINNED TUBE
      Tube material       : 90/10 CU/NI
      Pressure condition : VACUUM
      Nusselt theory is used for Ho

Ci (based on Petukhov-Popov)     =  2.8401
Alpha (based on Nusselt (Tdel)) =  0.8324
Enhancement (q)                  =  1.037
Enhancement (Del-T)              =  1.028
```

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.25	8.833E+03	1.300E+04	1.061E+05	8.16	49.03
2	3.73	9.031E+03	1.385E+04	1.010E+05	7.29	48.63
3	3.23	8.737E+03	1.384E+04	1.290E+05	9.32	48.51
4	2.72	8.156E+03	1.322E+04	1.455E+05	11.01	48.74
5	2.20	7.740E+03	1.317E+04	1.474E+05	11.19	48.76
6	1.68	7.169E+03	1.310E+04	1.465E+05	11.18	48.68
7	1.15	6.451E+03	1.337E+04	1.356E+05	10.15	48.96
8	1.15	6.337E+03	1.291E+04	1.350E+05	10.46	49.00
9	1.68	7.043E+03	1.270E+04	1.473E+05	11.60	48.85
10	2.20	7.560E+03	1.273E+04	1.562E+05	12.26	48.81
11	2.72	7.944E+03	1.277E+04	1.623E+05	12.71	48.88
12	3.25	8.297E+03	1.293E+04	1.649E+05	12.76	48.85
13	3.77	8.372E+03	1.257E+04	1.644E+05	13.08	49.15
14	4.29	8.511E+03	1.249E+04	1.661E+05	13.29	49.07

```
Least-squares line for q = a*delta-T^b
  a =  2.3683E+04
  b =  7.5000E-01


NOTE: 14 data points were stored in file VT051

NOTE: 14 X-Y pairs were stored in data file
```

```
NOTE: Program name : DRPALL
      Data taken by              : COBB
      This analysis done on file : VT061
      This analysis includes end-fin effect
      Thermal conductivity      =  55.3 (W/m.K)
      Inside diameter, Di       = 12.70 (mm)
      Outside diameter, Do      = 13.88 (mm)
      This analysis uses the QUARTZ THERMOMETER readings
      Modified Petukhov-Popov coefficient   = 2.5000
      Using HEATEX insert inside tube
      Tube Enhancement   : RECTANGULAR FINNED TUBE
      Tube material      : 90/10 CU/NI
      Pressure condition : VACUUM
      Nusselt theory is used for Ho

Ci (based on Petukhov-Popov)      =  2.3262
Alpha (based on Nusselt (Tdel)) =  1.0725
Enhancement (q)                   =  1.454
Enhancement (Del-T)               =  1.324
```

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	0.63	5.134E+03	1.704E+04	1.179E+05	6.92	48.75
2	1.16	6.952E+03	1.799E+04	1.669E+05	9.28	49.06
3	1.69	7.922E+03	1.720E+04	1.900E+05	11.04	48.64
4	2.21	8.478E+03	1.633E+04	2.070E+05	12.68	48.96
5	2.74	9.022E+03	1.626E+04	2.187E+05	13.45	48.69
6	3.27	9.282E+03	1.571E+04	2.264E+05	14.42	49.09
7	3.79	9.635E+03	1.572E+04	2.293E+05	14.59	48.60
8	4.32	9.778E+03	1.534E+04	2.299E+05	14.99	48.78
9	4.84	9.915E+03	1.510E+04	2.309E+05	15.30	48.93
10	4.84	9.875E+03	1.500E+04	2.307E+05	15.38	49.11
11	0.63	5.810E+03	2.491E+04	1.112E+05	4.46	48.88
12	1.15	7.270E+03	1.914E+04	1.378E+05	7.20	48.62
13	1.67	8.226E+03	1.793E+04	1.562E+05	8.71	48.53
14	1.67	8.098E+03	1.732E+04	1.555E+05	8.97	48.83

```
Least-squares line for q = a*delta-T^b
  a =  3.0792E+04
  b =  7.5000E-01


NOTE: 14 data points were stored in file VT061

NOTE: 14 X-Y pairs were stored in data file
```

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT063
This analysis includes end-fin effect
Thermal conductivity = 55.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : 90/10 CU/NI
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.4146
Alpha (based on Nusselt (Tdel)) = 1.0411
Enhancement (q) = 1.397
Enhancement (Del-T) = 1.285

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.32	9.577E+03	1.465E+04	2.270E+05	15.49	48.78
2	3.79	9.381E+03	1.481E+04	2.232E+05	15.07	48.76
3	1.68	7.859E+03	1.625E+04	1.827E+05	11.25	48.62
4	1.16	6.965E+03	1.710E+04	1.615E+05	9.45	48.85
5	3.27	9.230E+03	1.526E+04	2.199E+05	14.41	48.80
6	2.21	8.438E+03	1.570E+04	1.979E+05	12.61	48.65
7	2.74	8.920E+03	1.554E+04	2.103E+05	13.53	48.65
8	2.74	8.932E+03	1.558E+04	2.102E+05	13.50	48.64
9	2.21	8.408E+03	1.559E+04	1.977E+05	12.68	48.72
10	3.27	9.228E+03	1.525E+04	2.184E+05	14.32	48.70
11	1.68	7.797E+03	1.599E+04	1.831E+05	11.45	48.82
12	3.79	9.431E+03	1.494E+04	2.227E+05	14.91	48.56
13	1.16	7.004E+03	1.733E+04	1.631E+05	9.41	48.96
14	4.32	9.684E+03	1.491E+04	2.283E+05	15.32	48.68

Least-squares line for q = a*delta-T^b
a = 2.9617E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file VT063

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT071
This analysis includes end-fin effect
Thermal conductivity = 14.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : DEEP FILLET FINNED TUBE
Tube material : STAINLESS-STEEL
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.1088
Alpha (based on Nusselt (Tdel)) = 0.7827
Enhancement (q) = .955
Enhancement (Del-T) = .966

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.32	6.309E+03	1.157E+04	1.506E+05	13.02	48.89
2	1.16	4.898E+03	1.337E+04	1.133E+05	8.48	48.60
3	3.79	6.293E+03	1.199E+04	1.505E+05	12.56	48.73
4	1.68	5.355E+03	1.248E+04	1.262E+05	10.11	48.71
5	3.27	6.154E+03	1.210E+04	1.474E+05	12.18	48.69
6	2.21	5.662E+03	1.209E+04	1.347E+05	11.14	48.69
7	2.74	5.937E+03	1.208E+04	1.422E+05	11.77	48.70
8	2.74	5.928E+03	1.204E+04	1.425E+05	11.83	48.76
9	2.21	5.716E+03	1.234E+04	1.370E+05	11.10	48.74
10	3.27	6.162E+03	1.213E+04	1.486E+05	12.25	48.72
11	1.68	5.339E+03	1.241E+04	1.273E+05	10.26	48.74
12	3.79	6.256E+03	1.186E+04	1.523E+05	12.84	48.86
13	1.16	4.880E+03	1.328E+04	1.155E+05	8.69	48.79
14	4.32	6.318E+03	1.161E+04	1.519E+05	13.08	48.67

Least-squares line for q = a*delta-T^b
a = 2.2412E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file VT071

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT081
This analysis includes end-fin effect
Thermal conductivity = 14.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SHALLOW FILLET FINNED TUBE
Tube material : STAINLESS-STEEL
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.1523
Alpha (based on Nusselt (Tdel)) = 0.7957
Enhancement (q) = .977
Enhancement (Del-T) = .982

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.32	5.642E+03	1.174E+04	1.387E+05	11.81	48.79
2	1.16	4.419E+03	1.321E+04	1.063E+05	8.04	48.74
3	3.80	5.653E+03	1.229E+04	1.394E+05	11.34	48.71
4	1.69	4.850E+03	1.269E+04	1.180E+05	9.30	48.72
5	3.27	5.564E+03	1.254E+04	1.368E+05	10.91	48.65
6	2.21	5.191E+03	1.277E+04	1.275E+05	9.98	48.76
7	2.74	5.431E+03	1.279E+04	1.340E+05	10.48	48.78
8	2.74	5.424E+03	1.275E+04	1.339E+05	10.51	48.78
9	2.74	5.454E+03	1.291E+04	1.349E+05	10.45	48.83
10	4.32	5.694E+03	1.196E+04	1.389E+05	11.61	48.72
11	3.80	5.649E+03	1.226E+04	1.370E+05	11.18	48.69
12	3.27	5.608E+03	1.274E+04	1.356E+05	10.64	48.69
13	2.21	5.237E+03	1.303E+04	1.270E+05	9.75	48.72
14	2.21	5.214E+03	1.289E+04	1.268E+05	9.84	48.74
15	1.69	4.951E+03	1.339E+04	1.195E+05	8.92	48.66
16	1.16	4.495E+03	1.392E+04	1.080E+05	7.76	48.73

Least-squares line for q = a*delta-T^b
a = 2.2690E+04
b = 7.5000E-01

NOTE: 16 data points were stored in file VT081

NOTE: 16 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT091
This analysis includes end-fin effect
Thermal conductivity = 14.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : STAINLESS-STEEL
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 1.9382
Alpha (based on Nusselt (Tdel)) = 0.6872
Enhancement (q) = .803
Enhancement (Del-T) = .848

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.27	6.173E+03	1.117E+04	9.392E+04	8.41	48.88
2	3.75	6.163E+03	1.161E+04	9.927E+04	8.55	49.02
3	3.23	6.161E+03	1.224E+04	1.007E+05	8.22	48.70
4	2.71	5.894E+03	1.203E+04	9.625E+04	8.00	48.83
5	2.19	5.665E+03	1.224E+04	8.919E+04	7.29	48.67
6	1.66	5.332E+03	1.251E+04	8.122E+04	6.49	48.72
7	1.14	4.832E+03	1.308E+04	7.116E+04	5.44	48.72
8	1.14	4.849E+03	1.320E+04	7.089E+04	5.37	48.72

Least-squares line for q = a*delta-T^b
a = 1.9993E+04
b = 7.5000E-01

NOTE: 08 data points were stored in file VT091

NOTE: 08 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT093
This analysis includes end-fin effect
Thermal conductivity = 14.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : STAINLESS-STEEL
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 1.9365
Alpha (based on Nusselt (Tdel)) = 0.7823
Enhancement (q) = .955
Enhancement (Del-T) = .966

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.32	6.220E+03	1.162E+04	1.493E+05	12.85	48.79
2	1.15	4.754E+03	1.352E+04	1.070E+05	7.92	48.67
3	3.79	6.261E+03	1.224E+04	1.432E+05	11.70	48.67
4	1.68	5.325E+03	1.307E+04	1.170E+05	8.96	48.71
5	3.26	6.109E+03	1.231E+04	1.347E+05	10.94	48.56
6	2.20	5.671E+03	1.266E+04	1.230E+05	9.71	48.71
7	2.73	5.985E+03	1.273E+04	1.291E+05	10.14	48.60
8	2.73	5.952E+03	1.257E+04	1.291E+05	10.26	48.83

Least-squares line for q = a*delta-T^b
a = 2.2485E+04
b = 7.5000E-01

NOTE: 08 data points were stored in file VT093

NOTE: 08 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT094
This analysis includes end-fin effect
Thermal conductivity = 14.3 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : STAINLESS-STEEL
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 1.9238
Alpha (based on Nusselt (Tdel)) = 0.8485
Enhancement (q) = 1.064
Enhancement (Del-T) = 1.047

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.33	6.408E+03	1.237E+04	1.619E+05	13.09	48.89
2	1.16	4.817E+03	1.454E+04	1.138E+05	8.24	48.82
3	3.80	6.387E+03	1.290E+04	1.636E+05	12.68	48.91
4	1.69	5.404E+03	1.401E+04	1.356E+05	9.68	48.63
5	3.27	6.286E+03	1.330E+04	1.614E+05	12.14	48.93
6	2.22	5.693E+03	1.313E+04	1.452E+05	11.06	48.87
7	2.75	6.050E+03	1.334E+04	1.553E+05	11.64	48.93
8	2.75	6.108E+03	1.362E+04	1.563E+05	11.47	48.88
9	2.22	5.679E+03	1.306E+04	1.440E+05	11.03	48.70
10	3.27	6.199E+03	1.292E+04	1.580E+05	12.23	48.70
11	1.69	5.337E+03	1.357E+04	1.341E+05	9.88	48.63
12	3.80	6.350E+03	1.275E+04	1.640E+05	12.86	49.01
13	1.16	4.809E+03	1.449E+04	1.214E+05	8.38	49.09
14	4.33	6.476E+03	1.264E+04	1.665E+05	13.17	49.01

Least-squares line for q = a*delta-T^b
a = 2.4325E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file VT094

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT101
This analysis includes end-fin effect
Thermal conductivity = 231.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : ALUMINUM
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 1.9610
Alpha (based on Nusselt (Tdel)) = 1.3090
Enhancement (q) = 1.896
Enhancement (Del-T) = 1.616

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.32	1.173E+04	1.898E+04	2.739E+05	14.43	48.95
2	3.79	1.201E+04	2.113E+04	2.800E+05	13.25	48.76
3	3.23	1.207E+04	2.254E+04	2.010E+05	8.91	48.45
4	2.72	1.105E+04	2.171E+04	2.019E+05	9.30	48.85
5	2.19	1.031E+04	2.231E+04	1.814E+05	8.13	48.76
6	1.67	9.310E+03	2.305E+04	1.583E+05	6.87	48.81
7	1.15	8.029E+03	2.540E+04	1.334E+05	5.25	48.93
8	1.14	8.114E+03	2.624E+04	1.332E+05	5.08	48.81
9	1.67	9.408E+03	2.349E+04	1.534E+05	6.53	48.75
10	2.19	1.048E+04	2.284E+04	1.709E+05	7.48	48.78
11	2.71	1.116E+04	2.183E+04	1.798E+05	8.24	48.78
12	3.23	1.197E+04	2.204E+04	1.892E+05	8.59	48.66
13	3.75	1.232E+04	2.120E+04	1.922E+05	9.07	48.85
14	4.27	1.277E+04	2.103E+04	1.957E+05	9.31	48.86

Least-squares line for q = a*delta-T^b
a = 3.7884E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file VT101

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT103
This analysis includes end-fin effect
Thermal conductivity = 231.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : RECTANGULAR FINNED TUBE
Tube material : ALUMINUM
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.0284
Alpha (based on Nusselt (Tdel)) = 1.2990
Enhancement (q) = 1.877
Enhancement (Del-T) = 1.604

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.29	1.256E+04	2.034E+04	2.273E+05	11.18	48.74
2	3.76	1.238E+04	2.111E+04	2.147E+05	10.17	48.71
3	3.23	1.183E+04	2.118E+04	2.025E+05	9.57	49.03
4	2.71	1.124E+04	2.158E+04	1.888E+05	8.75	48.87
5	4.27	1.288E+04	2.096E+04	2.007E+05	9.58	48.59
6	1.14	8.074E+03	2.389E+04	1.244E+05	5.21	48.64
7	3.75	1.242E+04	2.112E+04	2.042E+05	9.67	48.74
8	1.15	8.219E+03	2.572E+04	1.371E+05	5.33	48.58
9	3.24	1.169E+04	2.086E+04	2.134E+05	10.23	48.98
10	1.67	9.493E+03	2.342E+04	1.718E+05	7.33	48.61
11	2.19	1.043E+04	2.220E+04	1.902E+05	8.57	48.53
12	2.72	1.109E+04	2.132E+04	2.074E+05	9.73	48.63
13	1.67	9.426E+03	2.316E+04	1.790E+05	7.73	48.94
14	2.20	1.023E+04	2.146E+04	1.968E+05	9.17	48.68

Least-squares line for q = a*delta-T^b
a = 3.7562E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file VT103

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT111
This analysis includes end-fin effect
Thermal conductivity = 231.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 13.88 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : DEEP FILLET FINNED TUBE
Tube material : ALUMINUM
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.3040
Alpha (based on Nusselt (Tdel)) = 1.1753
Enhancement (q) = 1.643
Enhancement (Del-T) = 1.451

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.31	1.091E+04	1.573E+04	2.471E+05	15.71	48.57
2	1.15	7.862E+03	1.977E+04	1.735E+05	8.78	48.68
3	3.79	1.127E+04	1.733E+04	2.560E+05	14.78	48.66
4	1.68	8.918E+03	1.830E+04	1.983E+05	10.84	48.64
5	3.26	1.088E+04	1.747E+04	2.464E+05	14.10	48.77
6	2.21	9.734E+03	1.783E+04	2.179E+05	12.22	48.74
7	2.73	1.051E+04	1.800E+04	2.347E+05	13.04	48.64
8	2.73	1.046E+04	1.787E+04	2.346E+05	13.13	48.75
9	2.21	9.788E+03	1.800E+04	2.183E+05	12.13	48.75
10	3.26	1.078E+04	1.720E+04	2.425E+05	14.09	48.76
11	1.68	8.980E+03	1.852E+04	1.985E+05	10.72	48.74
12	3.79	1.115E+04	1.703E+04	2.502E+05	14.69	48.71
13	1.15	7.881E+03	1.981E+04	1.732E+05	8.75	48.93
14	4.31	1.143E+04	1.681E+04	2.550E+05	15.17	48.70

Least-squares line for q = a*delta-T^b
a = 3.3489E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file VT111

NOTE: 14 X-Y pairs were stored in data file

NOTE: Program name : DRPALL
Data taken by : COBB
This analysis done on file : VT131
This analysis includes end-fin effect
Thermal conductivity = 231.8 (W/m.K)
Inside diameter, Di = 12.70 (mm)
Outside diameter, Do = 14.38 (mm)
This analysis uses the QUARTZ THERMOMETER readings
Modified Petukhov-Popov coefficient = 2.5000
Using HEATEX insert inside tube
Tube Enhancement : SHALLOW FILLET FINNED TUBE
Tube material : ALUMINUM
Pressure condition : VACUUM
Nusselt theory is used for Ho

Ci (based on Petukhov-Popov) = 2.2406
Alpha (based on Nusselt (Tdel)) = 1.0525
Enhancement (q) = 1.418
Enhancement (Del-T) = 1.299

Data #	Vw (m/s)	Uo (W/m^2-K)	Ho (W/m^2-K)	Qp (W/m^2)	Tcf (C)	Ts (C)
1	4.31	1.029E+04	1.502E+04	2.192E+05	14.59	48.66
2	1.15	7.262E+03	1.788E+04	1.519E+05	8.49	48.72
3	3.78	1.011E+04	1.534E+04	2.195E+05	14.30	48.79
4	1.68	8.122E+03	1.630E+04	1.738E+05	10.66	48.67
5	3.26	9.769E+03	1.547E+04	2.138E+05	13.82	48.74
6	2.21	8.820E+03	1.588E+04	1.910E+05	12.02	48.66
7	2.73	9.306E+03	1.552E+04	2.045E+05	13.17	48.75
8	2.73	9.313E+03	1.554E+04	2.041E+05	13.13	48.70
9	2.21	8.811E+03	1.587E+04	1.928E+05	12.15	48.72
10	3.26	9.756E+03	1.546E+04	2.140E+05	13.85	48.59
11	1.68	8.147E+03	1.644E+04	1.787E+05	10.87	48.89
12	3.78	1.002E+04	1.516E+04	2.213E+05	14.59	48.60
13	1.15	7.180E+03	1.752E+04	1.564E+05	8.92	48.93
14	4.31	1.023E+04	1.493E+04	2.243E+05	15.02	48.52

Least-squares line for q = a*delta-T^b
a = 2.3739E+04
b = 7.5000E-01

NOTE: 14 data points were stored in file VT131

NOTE: 14 X-Y pairs were stored in data file

APPENDIX E. UNCERTAINTY ANALYSIS

When measuring physical quantity, the actual value is unknown. There will always be a difference between the measured value of the quantity and the actual value. The magnitude of the difference depends on the accuracy of the measuring device and the level of experience of the operator of the device. Normally the error of measurement of a single calculation is rather small, however the error may grow in magnitude when combined with other measured quantities in a given calculation. The estimation of the difference between the actual and the calculated or measured value is known as the uncertainty of the obtained value.

The actual uncertainty is similar to the actual value, if you know one you can determine the other. Kline and McClintok [Ref. 38] developed a method to estimate the uncertainty in the obtained value. The method states for a quantity in some obtained value R, which is a function of several measured quantities ($R = R(x_1,x_2,x_3,\ldots,x_n)$), the uncertainty in R is given by the following relationship:

$$W_R=\left[\left(\frac{\partial R}{\partial x_1}W_1\right)^2+\left(\frac{\partial R}{\partial x_2}W_2\right)^2+\ldots\ldots+\left(\frac{\partial R}{\partial x_n}W_n\right)^2\right]^{1/2} \qquad \text{(E.1)}$$

where:

W_R = the uncertainty of the desired dependent variable

$x_1, x_2, \ldots x_n$ = the measured independent variables

$W_1, W_2, \ldots W_n$ = the uncertainties in the measured variables.

A complete description of the uncertainty analysis is given by Georgiadis [Ref. 39]. The uncertainty program, UNCERTCOBB, was a revision of Mitrou's [Ref. 14] uncertainty analysis program. The program is listed in this Appendix along with random data point analysis.

```
1000! FILE NAME : UNCERTCOBB
1005! REVISED :   SEPTEMBER 1993
1010!
1015  COM /Cc/ C(5)
1020  DIM E(20)
1025  DATA 273.15,2.5923E-2,-7.3933E-7,2.8625E-11
1026  DATA 1.9717E-15,-2.2486E-19
1035  READ C(*)
1040  PRINT
1045  PRINTER IS 701
1050  PRINT USING "15X,""DATA FOR THE UNCERTAINTY ANALYSIS:"""
1051  PRINT
1055  BEEP
1060  INPUT "ENTER FILE NAME",File$
1065  PRINT USING "15X,""File Name:                  "",12A";File$
1070  BEEP
1075  INPUT "ENTER DATA SET NUMBER FOR UNCERTAINTY ANALYSIS",Ids
1080  BEEP
1085  INPUT "ENTER PRESSURE CONDITION (0=V,1=A) ",Prc
1090  Prc=Prc+1
1095  BEEP
1100  INPUT "ENTER Ci",Ci
1105  ASSIGN @File TO File$
1110  ENTER @File;Ifg,Inn
1115  ENTER @File;Dd,Dd,Dd,Dd
1125  FOR I=1 TO Ids
1130  ENTER @File;Bvol,Bamp,Etp,Fm,Tci,Tco,Pvap1,Pvap2,E(*)
1131! PRINT Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,E(*)
1135  NEXT I
1140  Emf=E(0)
1145  IF Prc=1 THEN
1150  BEEP
1155  PRINT USING "15X,""Pressure Condition:   Vacuum (kPa)"""
1160  ELSE
1165  PRINT USING "15X,""Pressure Condition:   Atmospheric (kPa)"""
1170  END IF
1180  Ihi=0
1205  BEEP
1210  PRINTER IS 1
1211  PRINT "     SELECT INSIDE CORRELATION:"
1212  PRINT "        0= SIEDER-TATE (DEFAULT)"
1213  PRINT "        1= PETKHOV-POPOV"
1214  INPUT Ihi
1215  BEEP
1216  IF Ihi=0 THEN
1217  BEEP
1218  INPUT "  SELECT REYNOLDS EXPONENT",Rexp
```

```
1219 END IF
1220 BEEP
1222 PRINT USING "4X,""Select Material Code:"""
1223 PRINT USING "6X,""0 Copper    1 Stainless Steel"""
1225 PRINT USING "6X,""2 Aluminum  3 90:10 Cu-Ni"""
1230 PRINT USING "6X,""4 Titanium"""
1235 INPUT Itt
1240 IF Itt=0 THEN
1245 BEEP
1250 INPUT "SELECT (0=THIN, 1=THICK)",Iwt
1255 END IF
1260 PRINTER IS 701
1265 IF Itt=0 THEN
1266 INPUT "SELECT DIAMETER (0=SM, 1=MED, 2=LG)",Ds
1267 BEEP
1268 INPUT "SELECT FLUID (0=STEAM, 1=R-113, 2=EG)",Ifluid
1270 Di=.0127
1271 IF Ds=0 THEN
1272    Di=.0127
1273    Do=.01388
1274 END IF
1275 IF Ds=1 THEN
1276    Do=.01438
1277 END IF
1278 IF Ds=2 THEN
1279    Do=.0137
1280 END IF
1281 Kc=390.8
1282 Dkc=11.7
1285 IF Iwt=0 THEN
1290 Do=.01388
1295 ELSE
1300 Do=.01438     ! Outside diameter of test tube
1305 END IF
1310 END IF
1315 IF Itt=1 THEN
1320 Kc=14.3
1325 Dkc=.72
1330 Di=.0127
1335 Do=.01388
1340 END IF
1345 IF Itt=2 THEN
1350 Kc=231.8
1355 Dkc=9.3
1360 Do=.01388
1365 Di=.0127
1370 END IF
```

```
1375  IF Itt=3 THEN
1380  Kc=55.3
1385  Dkc=1.27
1390  Di=.0127
1395  Do=.01388
1400  END IF
1405  IF Itt=4 THEN
1410  Kc=18.9
1415  Dkc=.95
1420  Di=.01386
1425  Do=.01585
1430  END IF
1435  D1=.01585
1440  D2=.01585
1445  IF Itt=4 THEN D1=.01585
1446! IF Itt=1 THEN D1=.01585
1450  PRINTER IS 701
1455  Ts=FNTvsv(Emf)
1456  Ts=Ts-273.15
1460  PRINT USING "15X,""Vapor Temperature                    = "",4D.DDD,""        (Deg
 C)"""; Ts
1465  PRINT USING "15X,""Water Flow Rate (%)                  =  "",3D.2D"; Fm
1470  Dtci=.005
1475  Dtco=.005
1480  BEEP
1485  Demf=1.0E-6
1490  Dts=SQR(((C(1)+2*C(2)*Emf+3*C(3)*Emf^2+4*C(4)*Emf^3)*Demf)^2)
1495  T=(Tci+Tco)/2  ! FILM TEMPERATURE
1500! UNCERTAINTY IN THE COOLING WATER
1505  Drho=.5 ! ERROR IN WATER DENSITY
1510  Dmf=.0044 ! ERROR IN MASS FLOW RATE
1515  Rho=FNRho(T) ! WATER DENSITY
1520  Mf=(6.7409*Fm+13.027)/1000.! MASS FLOW RATE OF COOLING WATER
1525! CORRECT MF FOR THE TEMPERATURE EFFECT
1530  Mf=Mf*(1.0365-1.96644E-3*Tci+5.252E-6*Tci^2)/1.0037
1535  Ai=(PI*Di^2)/4 ! TUBE INSIDE CROSS SECTION AREA
1540  Ddi=.000025
1545  Dai=PI*Di*Ddi/2 ! ERROR OF INSIDE TUBE CROSS AREA
1550! COMPUTE THE WATER VELOCITY
1555  Vw=Mf/(Rho*Ai) ! WATER VELOCITY
1560  PRINT USING "15X,""Water Velocity                   =    "",Z.DD,""         (m/
s)"""; Vw
1565! CORRECT OUTLET WATER TEMP. FOR THE MIXING CHAMBER EFFECT
1566 IF Itt=0 THEN
1568  IF Inn=2 THEN Tco=Tco-(-3.99E-4+2.75E-3*Vw+1.45E-3*Vw^2+8.16E-5*Vw^3)
1570  IF Inn=1 THEN Tco=Tco-(-6.44E-5+1.71E-3*Vw+4.45E-4*Vw^2+4.07E-5*Vw^3)
1573  IF Inn=0 AND Vw>.5 THEN Tco=Tco-(-2.73E-4+1.75E-4*Vw+9.35E-4*Vw^2-1.96E-5*
Vw^3)
```

```
1576  END IF
1577  IF Itt=4 THEN  !TITANIUM TUBE
1578  IF Inn=0 AND Vw>.5 THEN Tco=Tco-(-4.62E-5-7.53E-4*Vw+1.80E-3*Vw^2-8.84E-5*
Vw^3)
1579  IF Inn=3 THEN Tco=Tco-(2.09E-4+9.74E-4*Vw+2.12E-3*Vw^2-3.31E-5*Vw^3)
1581  END IF
1584  IF Itt=1 THEN  ! LPD KORODENSE TITANIUM TUBE
1585  IF Inn=0 AND Vw>.5 THEN Tco=Tco-(-3.39E-4+1.88E-3*Vw+6.01E-4*Vw^2+4.13E-5*
Vw^3)
1586  IF Inn=3 THEN Tco=Tco-(2.09E-4+9.20E-4*Vw+1.89E-3*Vw^2-2.27E-5*Vw^3)
1588  END IF
1589  IF Inn=3 THEN
1590    Tco=Tco-(2.524E-5-1.696E-3*Vw+7.11E-3*Vw^2-3.32E-3*Vw^3+8.555E-4*Vw^4-7.
37E-5*Vw^5)
1591  END IF
1593  T=(Tci+Tco)*.5 !FILM TEMPERATURE
1594! PRINT Tci
1595! PRINT Tco
1596! PRINT Inn
1597! COMPUTE THE ERROR IN WATER VELOCITY
1598  Dvw=Vw*SQR((Dmf/Mf)^2+(Drho/Rho)^2+(Dai/Ai)^2)
1599! UNCERTAINTY IN THE REYNOLDS NUMBER
1600  Mw=FNMw(T) ! WATER VISCOSITY
1605  Dmw=6.E-6 ! ERROR OF WATER VISCOSITY
1610  Re=(Rho*Vw*Di)/Mw
1615  Dre=Re*SQR((Drho/Rho)^2+(Dvw/Vw)^2+(Ddi/Di)^2+(Dmw/Mw)^2)
1620! UNCERTAINTY IN THE HEAT TRANSFERRED
1625  Cpw=FNCpw(T)
1630  Q=Mf*(Tco-Tci)*Cpw
1635  Dcpw=8
1640  Dq=Q*SQR((Dmf/Mf)^2+((Dtco/(Tco-Tci)))^2+((Dtci/(Tco-Tci)))^2+(Dcpw/Cpw)^2
)
1645! UNCERTAINTY IN THE HEAT FLUX
1650  Dl=.0005 ! ERROR IN TUBE LENGTH
1655  Ddo=.000025
1660  L=.13335 ! CONDENSING TUBE LENGTH
1665  Qp=Q/(PI*Do*L) ! HEAT FLUX
1670  PRINT USING "15X,""Heat Flux                         =    "",Z.3DE,""  (W/m^2)"
"";Qp
1675  PRINT USING "15X,""Tube-metal thermal conduc.    =  "",3D.D,""         (W/m
.K)""";Kc
1680  PRINT USING "15X,""Petkhov-Popov constant=   "",Z.4D";C1
1685  Dqp=Qp*SQR((Dq/Q)^2+(Ddo/Do)^2+(Dl/L)^2)
1690  Lmtd=(Tco-Tci)/LOG((Ts-Tci)/(Ts-Tco))
1695  Uo=Qp/Lmtd ! OVERALL HEAT TRANSFER COEF.
1700  A1=Dts*(Tci-Tco)/((Ts-Tci)*(Ts-Tco)*LOG((Ts-Tci)/(Ts-Tco)))
1705  A2=Dtci/((Ts-Tci)*LOG((Ts-Tci)/(Ts-Tco)))
1710  A3=Dtco/((Ts-Tco)*LOG((Ts-Tci)/(Ts-Tco)))
```

```
1715 Dlmtd=Lmtd*SQR(A1^2+A2^2+A3^2)
1720 Duo=Uo*SQR((Dqp/Qp)^2+(Dlmtd/Lmtd)^2)
1725 M=Mw
1730 T1=(T+273.15)/273.15
1735 Kw=FNKw(T1)
1740 Ac=0.   ! INTERSCEPT FROM SIEDER PROGRAM
1745 L1=.060325 ! LENGTH OF UNFINNED LEFT PART OF TUBE
1750 L2=.034925 ! LENGTH OF UNFINNED RIGHT PART OF TUBE
1755 Pr=Cpw*Mw/Kw
1760 Muw=FNMuw(T)
1765! UNCERTAINTY OF INSIDE HEAT-TRANSFER COEFF.
1766 Cf=1.0
1768 IF Ihi=0 THEN
1775 Hi=(Kw/Di)*(Ci*Re^Rexp*Pr^.333*Cf+Ac)
1776 END IF
1777 IF Ihi=1 THEN
1778 Epsi=(1.82*LGT(Re)-1.64)^(-2)
1779 Ppk1=1.0+1.34*Epsi
1780 Ppk2=11.7+1.8*Pr^(-1/3)
1781 Pp1=(Epsi/8)*Re*Pr
1782 Pp2=(Ppk1+Ppk2*(Epsi/8)^.5*(Pr^(2/3)-1))
1783 Hi=(Kw/Di)*(Pp1/Pp2)
1784 END IF
1786 Dti=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
1787 Cfc=(Muw/FNMuw(T+Dti))^.14
1790 IF ABS((Cfc-Cf)/Cfc)>.01 THEN
1795 Cf=(Cf+Cfc)*.5
1800 GOTO 1775
1805 END IF
1810 P1=PI*(Di+D1)
1815 B1=(D1-Di)*PI*(Di+D1)*.5
1820 M1=(Hi*P1/(Kc*B1))^.5
1825 P2=PI*(Di+D2)
1830 B2=(D2-Di)*PI*(Di+D2)*.5
1835 M2=(Hi*P2/(Kc*B2))^.5
1840 Fe1=FNTanh(M1*L1)/(M1*L1)
1845 Fe2=FNTanh(M2*L2)/(M2*L2)
1850 Dtc=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
1855 IF ABS((Dtc-Dti)/Dtc)>.01 THEN 1775
1860 Dkw=.0010 ! ERROR IN WATER THERMAL CONDUCTIVITY
1865 IF Ifluid<2 THEN Dci=.002 ! ERROR IN SIEDER-TATE COEFFICIENT
1866 IF Ifluid=0 AND Ds=0 THEN Dci=.003
1867 IF Ifluid=2 THEN Dci=.005
1870 Dpr=.05 ! ERROR IN PRANDTL NUMBER
1875 Dcf=8.E-6
1880 A4=.14*Dcf/Cf
1885 Dhi=Hi*SQR((Dkw/Kw)^2+(Ddi/Di)^2+(.8*Dre/Re)^2+(.333*Dpr/Pr)^2+(Dci/Ci)^2+
A4)
```

```
1890! UNCERTAINTY OF OUTSIDE HEAT-TRANSFER COEFF.
1895  Rw=Do*LOG(Do/Di)/(2*Kc) ! WALL RESISTANCE
1900  Ho=1/((1/Uo)-(Do*L/(Di*(L+L1*Fe1+L2*Fe2)*Hi))-Rw)
1905  Drw=Rw*SQR((Ddo/Do)^2+(Dkc/Kc)^2+(Ddo/(Do*LOG(Do/Di)))^2+(Ddi/(Di*LOG(Do/D
i)))^2)
1910  A5=1/Uo-Rw-(Do*L/(Di*(L+L1*Fe1+L2*Fe2)*Hi))
1915  A6=Duo/(Uo^2*A5)
1920  A7=Drw/A5
1925  A8=((Do/(Di*Hi))*(Dhi/Hi))/A5
1930  PRINT
1935  Dho=Ho*SQR(A6^2+A7^2+A8^2)
1940! CALCULATE THE % UNCERTAINTY IN Ho
1945  Prho=Dho*100/Ho
1950! CALCULATE THE % UNCERTAINTY IN REYNOLDS NUMBER
1955  Prre=Dre*100/Re
1960! CALCULATE THE % UNCERTAINTY IN MASS FLOW RATE
1965  Prmf=Dmf*100/Mf
1970! CALCULATE THE % UNCERTAINTY IN HEAT TRANSFER
1975  Prqp=Dqp*100/Qp
1980! CALCULATE THE % UNCERTAINTY IN LMTD
1985  Prlmtd=Dlmtd*100/Lmtd
1990! CALCULATE THE % UNCERTAINTY IN Rw
1995  Prrw=Drw*100/Rw
2000! CALCULATE THE % UNCERTAINTY IN OVERALL HEAT TRANSFER COEF.
2005  Pruo=Duo*100/Uo
2010! CALCULATE THE % UNCERTAINTY IN INSIDE HEAT TRANSFER COEFF.
2015  Prhi=Dhi*100/Hi
2020  PRINT
2025  PRINT USING "15X,""UNCERTAINTY ANALYSIS:"""
2030  PRINT
2035  PRINT USING "15X,""    VARIABLE                   PERCENT UNCERTAINTY"""
2040  PRINT
2045  PRINT USING "15X,""Mass Flow Rate, Md                    "",Z.2D,";Prmf
2050  PRINT USING "15X,""Reynolds Number, Re                   "",Z.2D,";Prre
2055  PRINT USING "15X,""Heat Flux, q                         "",DD.2D,";Prqp
2060  PRINT USING "15X,""Log-Mean-Tem Diff, LMTD              "",DD.2D";Prlmtd
2065  PRINT USING "15X,""Wall Resistance, Rw                  "",DD.2D,";Prrw
2070  PRINT USING "15X,""Overall H.T.C., Uo                   "",DD.2D,";Pruo
2075  PRINT USING "15X,""Water-Side H.T.C., Hi               "",3D.2D,";Prhi
2080  PRINT USING "15X,""Vapor-Side H.T.C., Ho               "",3D.2D,";Prho
2085  END
2090  DEF FNMuw(T)
2095  A=247.8/(T+133.15)
2100  Muw=2.4E-5*10^A
2105  RETURN Muw
2110  FNEND
2115  DEF FNTanh(X)
```

```
2120  P=EXP(X)
2125  Q=EXP(-X)
2130  Tanh=(P-Q)/(P+Q)
2135  RETURN Tanh
2140  FNEND
2145  DEF FNKw(T1)
2150  Kw=-.92247+T1*(2.8395-T1*(1.8007-T1*(.52577-.07344*T1)))
2155  RETURN Kw
2160  FNEND
2165  DEF FNMw(T)
2170  A=247.8/(T+133.15)
2175  Mw=2.4E-5*10^A
2180  RETURN Mw
2185  FNEND
2190  DEF FNRho(T)
2195  Rho=999.52946+T*(.01269-T*(5.482513E-3-T*1.234147E-5))
2200  RETURN Rho
2205  FNEND
2210  DEF FNCpw(T)
2215  Cpw=(4.21120858-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7*T)))*1000
2220  RETURN Cpw
2225  FNEND
2230  DEF FNTvsv(Emf)
2235  COM /Cc/ C(5)
2240  T=C(0)
2245  FOR I=1 TO 5
2250  T=T+C(I)*Emf^I
2255  NEXT I
2260  RETURN T
2265  FNEND
```

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT013		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	99.862	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.26	(m/s)
Heat Flux	=	1.225E+06	(W/m^2)
Tube-metal thermal conduc.	=	390.8	(W/m.K)
Petkhov-Popov constant=	3.1616		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.82
Reynolds Number, Re	1.28
Heat Flux, q	.97
Log-Mean-Tem Diff, LMTD	.22
Wall Resistance, Rw	4.24
Overall H.T.C., Uo	.99
Water-Side H.T.C., Hi	1.13
Vapor-Side H.T.C., Ho	64.50

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT013		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	100.069	(Deg C)
Water Flow Rate (%)	=	70.00	
Water Velocity	=	3.74	(m/s)
Heat Flux	=	1.160E+06	(W/m^2)
Tube-metal thermal conduc.	=	390.8	(W/m.K)
Petkhov-Popov constant=	3.1616		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.94
Reynolds Number, Re	1.37
Heat Flux, Q	1.06
Log-Mean-Tem Diff, LMTD	.21
Wall Resistance, Rw	4.24
Overall H.T.C., Uo	1.08
Water-Side H.T.C., Hi	1.19
Vapor-Side H.T.C., Ho	22.71

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT013		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	99.969	(Deg C)
Water Flow Rate (%)	=	50.00	
Water Velocity	=	2.70	(m/s)
Heat Flux	=	1.092E+06	(W/m^2)
Tube-metal thermal conduc.	=	390.8	(W/m.K)
Petkhov-Popov constant=	3.1616		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	1.29
Reynolds Number, Re	1.62
Heat Flux, q	1.38
Log-Mean-Tem Diff, LMTD	.16
Wall Resistance, Rw	4.24
Overall H.T.C., Uo	1.39
Water-Side H.T.C., Hi	1.37
Vapor-Side H.T.C., Ho	8.11

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: AT013
Pressure Condition: Atmospheric (kPa)

Vapor Temperature	=	100.014	(Deg C)
Water Flow Rate (%)	=	20.00	
Water Velocity	=	1.15	(m/s)
Heat Flux	=	7.864E+05	(W/m^2)
Tube-metal thermal conduc.	=	390.8	(W/m.K)

Petkhov-Popov constant= 3.1616

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.05
Reynolds Number, Re	3.20
Heat Flux, q	3.09
Log-Mean-Tem Diff, LMTD	.09
Wall Resistance, Rw	4.24
Overall H.T.C., Uo	3.09
Water-Side H.T.C., Hi	2.60
Vapor-Side H.T.C., Ho	7.70

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT061		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	99.994	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.27	(m/s)
Heat Flux	=	7.277E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)
Petkhov-Popov constant=	2.7938		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.82
Reynolds Number, Re	1.25
Heat Flux, q	1.01
Log-Mean-Tem Diff, LMTD	.38
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	1.08
Water-Side H.T.C., Hi	1.09
Vapor-Side H.T.C., Ho	4.98

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT061		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	99.727	(Deg C)
Water Flow Rate (%)	=	20.00	
Water Velocity	=	1.15	(m/s)
Heat Flux	=	5.480E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)
Petkhov-Popov constant=	2.7938		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.02
Reynolds Number, Re	3.15
Heat Flux, q	3.06
Log-Mean-Tem Diff, LMTD	.14
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	3.07
Water-Side H.T.C., Hi	2.55
Vapor-Side H.T.C., Ho	12.27

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: AT063
Pressure Condition: Atmospheric (kPa)

Vapor Temperature	=	99.870	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.29	(m/s)
Heat Flux	=	7.452E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)

Petkhov-Popov constant= 2.5534

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.81
Reynolds Number, Re	1.20
Heat Flux, Q	1.00
Log-Mean-Tem Diff, LMTD	.37
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	1.07
Water-Side H.T.C., Hi	1.05
Vapor-Side H.T.C., Ho	4.76

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: AT063
Pressure Condition: Atmospheric (kPa)

Vapor Temperature	=	100.099	(Deg C)
Water Flow Rate (%)	=	70.00	
Water Velocity	=	3.77	(m/s)
Heat Flux	=	7.313E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)

Petkhov-Popov constant= 2.5534

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.93
Reynolds Number, Re	1.28
Heat Flux, q	1.08
Log-Mean-Tem Diff, LMTD	.33
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	1.13
Water-Side H.T.C., Hi	1.11
Vapor-Side H.T.C., Ho	6.31

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT063		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	100.011	(Deg C)
Water Flow Rate (%)	=	50.00	
Water Velocity	=	2.72	(m/s)
Heat Flux	=	6.835E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)
Petkhov-Popov constant=	2.5534		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	1.28
Reynolds Number, Re	1.56
Heat Flux, Q	1.39
Log-Mean-Tem Diff, LMTD	.26
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	1.41
Water-Side H.T.C., Hi	1.32
Vapor-Side H.T.C., Ho	22.05

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT063		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	99.928	(Deg C)
Water Flow Rate (%)	=	20.00	
Water Velocity	=	1.15	(m/s)
Heat Flux	=	5.289E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)
Petkhov-Popov constant=	2.5534		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.04
Reynolds Number, Re	3.17
Heat Flux, Q	3.08
Log-Mean-Tem Diff, LMTD	.14
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	3.08
Water-Side H.T.C., Hi	2.58
Vapor-Side H.T.C., Ho	13.12

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT094		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	99.986	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.29	(m/s)
Heat Flux	=	5.103E+05	(W/m^2)
Tube-metal thermal conduc.	=	14.3	(W/m.K)
Petkhov-Popov constant=	2.0961		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.81
Reynolds Number, Re	1.20
Heat Flux, Q	1.08
Log-Mean-Tem Diff, LMTD	.54
Wall Resistance, Rw	5.87
Overall H.T.C., Uo	1.21
Water-Side H.T.C., Hi	1.05
Vapor-Side H.T.C., Ho	8.37

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT094		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	99.924	(Deg C)
Water Flow Rate (%)	=	50.00	
Water Velocity	=	2.72	(m/s)
Heat Flux	=	4.813E+05	(W/m^2)
Tube-metal thermal conduc.	=	14.3	(W/m.K)
Petkhov-Popov constant=	2.0961		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	1.28
Reynolds Number, Re	1.56
Heat Flux, Q	1.41
Log-Mean-Tem Diff, LMTD	.36
Wall Resistance, Rw	5.87
Overall H.T.C., Uo	1.46
Water-Side H.T.C., Hi	1.32
Vapor-Side H.T.C., Ho	19.08

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT094		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	99.808	(Deg C)
Water Flow Rate (%)	=	20.00	
Water Velocity	=	1.15	(m/s)
Heat Flux	=	3.840E+05	(W/m^2)
Tube-metal thermal conduc.	=	14.3	(W/m.K)
Petkhov-Popov constant=	2.0961		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.04
Reynolds Number, Re	3.16
Heat Flux, q	3.08
Log-Mean-Tem Diff, LMTD	.19
Wall Resistance, Rw	5.87
Overall H.T.C., Uo	3.08
Water-Side H.T.C., Hi	2.57
Vapor-Side H.T.C., Ho	23.75

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT101		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	100.001	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.27	(m/s)
Heat Flux	=	9.614E+05	(W/m^2)
Tube-metal thermal conduc.	=	231.8	(W/m.K)
Petkhov-Popov constant=	2.3854		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.82
Reynolds Number, Re	1.25
Heat Flux, Q	.98
Log-Mean-Tem Diff, LMTD	.29
Wall Resistance, Rw	5.01
Overall H.T.C., Uo	1.02
Water-Side H.T.C., Hi	1.10
Vapor-Side H.T.C., Ho	7.43

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	AT101		
Pressure Condition:	Atmospheric (kPa)		
Vapor Temperature	=	100.146	(Deg C)
Water Flow Rate (%)	=	50.00	
Water Velocity	=	2.72	(m/s)
Heat Flux	=	8.834E+05	(W/m^2)
Tube-metal thermal conduc.	=	231.8	(W/m.K)
Petkhov-Popov constant=	2.3854		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	1.28
Reynolds Number, Re	1.57
Heat Flux, q	1.38
Log-Mean-Tem Diff, LMTD	.20
Wall Resistance, Rw	5.01
Overall H.T.C., Uo	1.39
Water-Side H.T.C., Hi	1.33
Vapor-Side H.T.C., Ho	47.40

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT094		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.927	(Deg C)
Water Flow Rate (%)	=	50.00	
Water Velocity	=	2.75	(m/s)
Heat Flux	=	1.512E+05	(W/m^2)
Tube-metal thermal conduc.	=	14.3	(W/m.K)
Petkhov-Popov constant=	1.9238		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	1.27
Reynolds Number, Re	1.49
Heat Flux, Q	1.78
Log-Mean-Tem Diff, LMTD	1.17
Wall Resistance, Rw	5.87
Overall H.T.C., Uo	2.13
Water-Side H.T.C., Hi	1.26
Vapor-Side H.T.C., Ho	12.04

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT094	
Pressure Condition:	Vacuum (kPa)	
Vapor Temperature	= 48.822	(Deg C)
Water Flow Rate (%)	= 20.00	
Water Velocity	= 1.16	(m/s)
Heat Flux	= 1.194E+05	(W/m^2)
Tube-metal thermal conduc.	= 14.3	(W/m.K)
Petkhov-Popov constant=	1.9238	

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.01
Reynolds Number, Re	3.11
Heat Flux, q	3.10
Log-Mean-Tem Diff, LMTD	.62
Wall Resistance, Rw	5.87
Overall H.T.C., Uo	3.17
Water-Side H.T.C., Hi	2.52
Vapor-Side H.T.C., Ho	60.75

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT094		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	49.091	(Deg C)
Water Flow Rate (%)	=	20.00	
Water Velocity	=	1.16	(m/s)
Heat Flux	=	1.210E+05	(W/m^2)
Tube-metal thermal conduc.	=	14.3	(W/m.K)
Petkhov-Popov constant=	1.9238		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.01
Reynolds Number, Re	3.11
Heat Flux, q	3.10
Log-Mean-Tem Diff, LMTD	.62
Wall Resistance, Rw	5.87
Overall H.T.C., Uo	3.16
Water-Side H.T.C., Hi	2.52
Vapor-Side H.T.C., Ho	61.42

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT103		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.738	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.29	(m/s)
Heat Flux	=	2.274E+05	(W/m^2)
Tube-metal thermal conduc.	=	231.8	(W/m.K)
Petkhov-Popov constant=	2.0284		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.81
Reynolds Number, Re	1.20
Heat Flux, q	1.53
Log-Mean-Tem Diff, LMTD	1.21
Wall Resistance, Rw	5.01
Overall H.T.C., Uo	1.95
Water-Side H.T.C., Hi	1.06
Vapor-Side H.T.C., Ho	7.43

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT103		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.628	(Deg C)
Water Flow Rate (%)	=	50.00	
Water Velocity	=	2.72	(m/s)
Heat Flux	=	2.074E+05	(W/m^2)
Tube-metal thermal conduc.	=	231.8	(W/m.K)
Petkhov-Popov constant=	2.0284		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	1.28
Reynolds Number, Re	1.55
Heat Flux, q	1.60
Log-Mean-Tem Diff, LMTD	.84
Wall Resistance, Rw	5.01
Overall H.T.C., Uo	1.81
Water-Side H.T.C., Hi	1.32
Vapor-Side H.T.C., Ho	23.78

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT103		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.637	(Deg C)
Water Flow Rate (%)	=	20.00	
Water Velocity	=	1.14	(m/s)
Heat Flux	=	1.244E+05	(W/m^2)
Tube-metal thermal conduc.	=	231.8	(W/m.K)
Petkhov-Popov constant=		2.0284	

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.05
Reynolds Number, Re	3.19
Heat Flux, Q	3.14
Log-Mean-Tem Diff, LMTD	.59
Wall Resistance, Rw	5.01
Overall H.T.C., Uo	3.20
Water-Side H.T.C., Hi	2.59
Vapor-Side H.T.C., Ho	18.77

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: AT101
Pressure Condition: Atmospheric (kPa)
Vapor Temperature = 100.108 (Deg C)
Water Flow Rate (%) = 20.00
Water Velocity = 1.15 (m/s)
Heat Flux = 6.394E+05 (W/m^2)
Tube-metal thermal conduc. = 231.8 (W/m.K)
Petkhov-Popov constant= 2.3854

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.04
Reynolds Number, Re	3.18
Heat Flux, Q	3.08
Log-Mean-Tem Diff, LMTD	.12
Wall Resistance, Rw	5.01
Overall H.T.C., Uo	3.08
Water-Side H.T.C., Hi	2.58
Vapor-Side H.T.C., Ho	10.78

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT011		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.675	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.32	(m/s)
Heat Flux	=	3.485E+05	(W/m^2)
Tube-metal thermal conduc.	=	390.8	(W/m.K)
Petkhov-Popov constant=	2.9862		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.81
Reynolds Number, Re	1.14
Heat Flux, q	1.22
Log-Mean-Tem Diff, LMTD	.80
Wall Resistance, Rw	4.24
Overall H.T.C., Uo	1.46
Water-Side H.T.C., Hi	1.00
Vapor-Side H.T.C., Ho	10.92

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT011		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.541	(Deg C)
Water Flow Rate (%)	=	40.00	
Water Velocity	=	2.21	(m/s)
Heat Flux	=	2.843E+05	(W/m^2)
Tube-metal thermal conduc.	=	390.8	(W/m.K)
Petkhov-Popov constant=	2.9862		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	1.58
Reynolds Number, Re	1.77
Heat Flux, q	1.71
Log-Mean-Tem Diff, LMTD	.50
Wall Resistance, Rw	4.24
Overall H.T.C., Uo	1.79
Water-Side H.T.C., Hi	1.47
Vapor-Side H.T.C., Ho	15.03

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT063		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.775	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.32	(m/s)
Heat Flux	=	2.270E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)
Petkhov-Popov constant=	2.4146		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.81
Reynolds Number, Re	1.14
Heat Flux, q	1.53
Log-Mean-Tem Diff, LMTD	1.22
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	1.96
Water-Side H.T.C., Hi	1.00
Vapor-Side H.T.C., Ho	6.33

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT063		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.759	(Deg C)
Water Flow Rate (%)	=	70.00	
Water Velocity	=	3.79	(m/s)
Heat Flux	=	2.233E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)
Petkhov-Popov constant=	2.4146		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.92
Reynolds Number, Re	1.23
Heat Flux, q	1.50
Log-Mean-Tem Diff, LMTD	1.09
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	1.85
Water-Side H.T.C., Hi	1.06
Vapor-Side H.T.C., Ho	7.19

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT063		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.651	(Deg C)
Water Flow Rate (%)	=	50.00	
Water Velocity	=	2.74	(m/s)
Heat Flux	=	2.103E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)
Petkhov-Popov constant=	2.4146		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	1.27
Reynolds Number, Re	1.51
Heat Flux, Q	1.59
Log-Mean-Tem Diff, LMTD	.84
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	1.80
Water-Side H.T.C., Hi	1.28
Vapor-Side H.T.C., Ho	15.43

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT063		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.855	(Deg C)
Water Flow Rate (%)	=	20.00	
Water Velocity	=	1.16	(m/s)
Heat Flux	=	1.615E+05	(W/m^2)
Tube-metal thermal conduc.	=	55.3	(W/m.K)
Petkhov-Popov constant=	2.4146		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.01
Reynolds Number, Re	3.12
Heat Flux, q	3.08
Log-Mean-Tem Diff, LMTD	.46
Wall Resistance, Rw	3.78
Overall H.T.C., Uo	3.12
Water-Side H.T.C., Hi	2.53
Vapor-Side H.T.C., Ho	16.40

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT091		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.876	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.27	(m/s)
Heat Flux	=	7.970E+04	(W/m^2)
Tube-metal thermal conduc.	=	14.3	(W/m.K)
Petkhov-Popov constant=	1.9382		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.82
Reynolds Number, Re	1.24
Heat Flux, Q	3.57
Log-Mean-Tem Diff, LMTD	3.44
Wall Resistance, Rw	5.87
Overall H.T.C., Uo	4.95
Water-Side H.T.C., Hi	1.09
Vapor-Side H.T.C., Ho	10.64

DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	VT094		
Pressure Condition:	Vacuum (kPa)		
Vapor Temperature	=	48.892	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	4.33	(m/s)
Heat Flux	=	1.471E+05	(W/m^2)
Tube-metal thermal conduc.	=	14.3	(W/m.K)
Petkhov-Popov constant=	1.9238		

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.80
Reynolds Number, Re	1.13
Heat Flux, q	2.11
Log-Mean-Tem Diff, LMTD	1.89
Wall Resistance, Rw	5.87
Overall H.T.C., Uo	2.83
Water-Side H.T.C., Hi	.99
Vapor-Side H.T.C., Ho	8.09

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